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CONTENTS.

PAGE

One Hundred and Forty-Sixth General Meeting :—

New Methods of Dewaxing and Acid Refining Mineral Oils, by Dr. NILS OLAF BACKLUND 1

Discussion : T. DEWHURST, J. MCCONNELL SANDERS, Dr. F. B. THOLE, Lieut.-Colonel S. J. M. AULD, Dr. F. H. GARNER, E. THORNTON, J. E. HACKFORD, H. MOORE 15

Contributed Discussion : A. A. ASHWORTH 21

Reply by Dr. N. O. BACKLUND 22

Integration and Pulsation Errors in Measurement of Quantities of Gas Flowing Through an Orifice, by D. GILMOUR.. 25

Trinidad Branch :—

Second Annual Dinner 69

Books Received : " Index to A.S.T.M. Standards and Tentative Standards " ; " Report of Further Tests by the Director of Fuel Research on the Turner Retort, Installed at the Works of the Comac Oil Co., Ltd., Coalburn, Lancashire " ; " Petroleum Vademecum," by R. SCHWARTZ .. 72

One Hundred and Forty-Seventh General Meeting :—

Aircraft in Relation to Petroleum Technology : Use for Survey and Transport, by H. HEMMING, A.F.C., F.R.G.S., A.F.R.Ae.S. 73

Discussion : THE PRESIDENT, ROBERT ANNAN, Major B. DAY, R. BOURNE, Wing-Commander F. C. V. LAWS, Flight-Lieutenant CAMPBELL, Dr. A. WADE, T. R. H. GARRETT, C. A. P. SOUTHWELL, T. DEWHURST, D. A. SUTHERLAND 97

Contributed Discussion : C. T. BERRY, L. OWEN 110

Reply by H. HEMMING 112

The Origin and Environment of Petroleum Source Sediments, by M. E. KELLY 117

Rumanian Branch :—

Discussion on " Some Observations on the Study of an Oilfield " : J. L. CHAILLET, G. ELIAS, C. M. POLLOCK, Mr. METCH, A. A. PEREBINOSSOFF, C. M. LEITCH .. 142

Reply by J. W. WEIL 147

CONTENTS.

PAGE

Reviews : " The Catalytic Oxidation of Organic Compounds in the Vapour Phase," by L. F. MAREK and D. A. HAHN ; " Bituminous Emulsions for Use in Road Works," by F. WILKINSON and F. J. FORTY ; " Le Petrole en Roumanie," by MIHAIL PIZANTY ; " British Chemicals and their Manufacture " ; " Official Directory of the British Chemical Plant Manufacturers Association, 1933 " .. 149

One Hundred and Forty-Eighth General Meeting :—

Candles and Candlemaking, by DAVID ALLAN, F.I.C., A.R.T.C. 155

Discussion : THE PRESIDENT, J. GILLESPIE, E. R. REDGROVE, T. R. H. GARRETT 171

Reply by DAVID ALLAN 174

Investigation into the Plastic Properties of Asphaltic Bitumen, by R. N. J. SAAL and G. KOENS 176

Combustion and Injection in High-Speed Compression-Ignition Engines, by D. A. C. DEWDNEY 213

The Occurrence, Nature and Origin of Asphaltites in Limestone and Oil Shale Deposits in Estonia, by PAUL N. KOGERMAN, M.Sc., D.I.C. 215

Contributed Discussion on " Some Observations on the Study of an Oilfield " : Dr. T. SUTTON BOWMAN 223

Reviews : " Annual Reports of the Progress of Applied Chemistry " ; " Lubricating and Allied Oils " (2nd Edition), by E. A. EVANS 227

One Hundred and Forty-Ninth General Meeting :—

The Migration of Oil and Natural Gas, by Prof. V. C. ILLING, M.A., M.Inst.M.M., F.G.S. 229

Discussion : A. BEEBY THOMPSON, J. ROMANES, E. H. CUNNINGHAM-CRAIG, Dr. A. WADE, T. DEWHURST, L. OWEN 260

Contributed Discussion : J. C. TEMPLETON 268

Reply by Prof. V. C. ILLING 269

Annual Report of the Council, 1932 275

Twentieth Annual General Meeting 285

Presidential Address, by T. DEWHURST 297

The Use of Synthetic Methanol as a Motor Fuel, by DONALD A. HOWES, Ph.D., B.Sc. 301

CONTENTS.

	PAGE
Reviews : " Chemistry and Technology of Cracking," by A. N. Sachanen ; " Origin and Environment of Source Sediments of Petroleum," by Parker D. Trask	332
Knock-Rating of Motor Fuels..	334
One Hundred and Fiftieth General Meeting :—	
An Analytical Steam Distillation for Measuring the Volatility Range of Lubricating Oils and other High-Boiling Petroleum Fractions, by R. N. J. Saal and C. G. Verver	336
Discussion : Dr. F. B. Thole, A. A. Ashworth, E. R. Redgrove, E. A. Evans, F. H. Garner, E. M. Shipman, J. S. Jackson	354
Reply by R. N. J. Saal and C. G. Verver	361
A Study of the Refining of a Burmah Crude Oil with Special Regard to the Colour Reversion Characteristics of the Lubricating Oil Distillates, by A. R. Bowen, M.Sc., Ph.D., F.I.C.	364
The Simplest and Most Accurate Viscometer, and other Instruments with Suspended Level, by Prof. Dr. L. Ubbelohde	376
One Hundred and Fifty-First General Meeting :— The World Petroleum Congress	423
Correspondence : " The Migration of Oil and Natural Gas " ..	425
Book Received : " Chemical Engineering and Chemical Catalogue "	426
Reports on the Progress of Naphthology, 1932 :—	
Geology of Petroleum, by Prof. V. C. Illing, M.A., M.Inst.M.M., F.G.S.	427
Geophysics, by Oscar Weiss	437
Field Technology, edited by B. J. Ellis :—	
Drilling :	
Rotary Drilling, by Robert Harcus, A.M.I.Min.E.	448
Rotary Drilling Mud, by Alexander Reid.. ..	455
Water Location During Drilling, by Alexander Reid	458
Cable Tool Drilling	459
Well Equipment, by W. Wade, A.M.I.Mech.E. ..	459
Cement, by A. Reid	461
Well Surveying, by P. Evans, B.A., F.G.S. ..	463
Power	466

PAGE

Reports on the Progress of Naphthology—*continued.*
Production :
Gas Lift Methods, by L. W. Rogers 467
Flowing Methods 470
Care of Wells, by Cyril Thomas, B.Sc. 473
Well Surveying, by Captain D. Comins, M.C. .. 474
Gas and Oil Separation, by G. McConnell 476
Water and Oil Separation 476
Gas Treatment, by V. V. Jacomini 477
Oil Mining, by A. Pellissier.. 477
Transportation and Storage :
Pipe Lines, by A. C. Hartley, A.C.G.I., M.Inst.C.E., M.I.Mech.E. 479
Tank Steamers, by Douglas H. Jackson, M.I.Mar.Eng., M.I.N.A. 491
Natural Gas Transport, by A. C. Hartley, A.C.G.I., M.Inst.C.E., M.I.Mech.E. 492
Storage, by A. C. Hartley, A.C.G.I., M.Inst.C.E., M.I.Mech.E. 494
Oil Measurement 495
Fire Prevention and Fire Fighting 496
Refining, by W. J. Wilson, F.I.C., A.C.G.I. 497
The Cracking Art in 1932, by Gustav Egloff, Ph.D., M.A., M.Am.Inst.Chem.E., M.Am.Chem.Soc., and Badona L. Levinson 504
Distillation and Fractionation Equipment, by Dr. R. K. Fischer 529
Chemical and Physical Refining, by B. C. Allibone, A.R.C.Sc., B.Sc., A.I.C. 539
Natural Gas and Natural Gasoline, by Miss Thelma Hoffman 549
Crude Oil, by W. H. Thomas, A.R.S.M. 554
Motor Spirits and Light Distillates, by D. A. Howes, Ph.D., B.Sc. 557
Gasoline Engines and Knock Testing, by R. Stansfield, A.M.Inst.C.E. 567
Kerosine and White Spirit, by S. T. Minchin 574
Lubricants and Lubrication, by A. R. Bowen, D.Sc., Ph.D., F.I.C. 578

PAGE

Reports on the Progress of Naphthology—*continued.*

467 Gas Oil, Diesel Fuel Oil and Fuel Oil, by F. H. GARNER, Ph.D., M.Sc., F.I.C. 592

470 Oil Engine Development, by P. N. EVERETT, A.M.Inst.C.E. 600

473 Asphalts and Road Materials, by W. W. GOULSTON, B.A.,
474 B.Sc., A.I.C. 617

476 Special Products, by E. B. EVANS, M.Sc., A.I.C. 628

476 Analysis and Testing, by W. H. THOMAS, A.R.S.M. .. 636

477 Standard Methods of Testing Petroleum and its Products,
477 by Prof. J. S. S. BRAME, C.B.E., F.I.C., F.C.S... .. 652

Chemistry of Petroleum, by D. A. HOWES, Ph.D., B.Sc... 655

Statistics, by GEORGE SELL.. 673

479 Some Methods in Oilfield Water Analysis, by W. A. MACFADYEN, M.C., Ph.D., F.G.S. 679

491 Principles of Gaslift, by JAN VERSLUYS 687

492 Conditions under which Gas and Liquid Mixtures Rise, by JAN VERSLUYS 694

494 The Analysis of Hydrocarbon Oils, by R. H. GRIFFITH and H. HOLLINGS 701

495 The Performance of High-Speed Diesel Engines for Road
496 Transport as Affected by the Nature of the Fuel, by J. G.
497 WITHERS, B.Sc., A.Inst.P. 713

Railway Traction in Relation to the Oil Industry, by G. M. BARRETT, B.Sc. 725

504 Rumanian Branch :—
Sixth Annual Dinner 733

529 Correspondence : " The Migration of Oil and Natural Gas " ;
" Bituminous Emulsions for Use in Road Works " .. 740

539 Trinidad Branch :—
Fifth Annual General Meeting :

549 Contribution to the Knowledge of Sedimentary
554 Volcanism in Trinidad, by H. G. KUGLER, Ph.D., F.G.S. 743

557 *Discussion :* A. J. RUTHVEN MURRAY, G. A. RICHARDS, G. H. SCOTT, Dr. REVERTERA, C. C. WILSON, E. C. SCOTT, E. LEHNER, G. W. HALSE, P. W. JARVIS, M. AP RHYS
567 PRICE 760

574 Reply by Dr. H. G. KUGLER 770

578 The Conversion of Fatty and Waxy Substances into Petroleum Hydrocarbons, by W. F. SEYER 773

CONTENTS.

PAGE

Catalytic High Pressure Hydrogenation of Aromatic Hydrocarbons and Catalytic High Pressure Destruction of the Corresponding Hydrogenated Products ; II., Mesitylene ; III., Hexamethylbenzene, by A. Dros, A. J. Tulleners and H. I. Waterman 784

Polymerisation and Explosive Decomposition of Ethylene under Pressure, by Gustav Egloff, Ph.D., M.A., M.Am.Inst.Chem.E., M.Am.Chem.Soc., and R. E. Schaad 800

Smoke Point of Kerosine.. 812

Reviews : " The Geology of California," by Ralph D. Reed ; " The R.E.F.U.T.A.S. Viscosity-Temperature Chart " ; " The Analysis of Oil for the Production of Lubricants," by A. A. Ashworth ; " Earth Oil," by Gustav Egloff 815

A Theoretical Comparison of Petroleum Distillation Systems, by Percy Meyer, B.Sc., F.I.C. 819

Ozone, Knock-Inducer Extraordinary, by Donald B. Brooks 835

A Contribution to the Study of Oil-Field Water Analysis, by Abol Hassan Khan Radjy, B.Sc., and Charles Edmund Wood, M.Sc. 845

Trinidad Branch :—

Twenty-Seventh General Meeting :

Discussion on " Behaviour of Restricted Wells " ; C. E. Capito, Albert Millar, G. H. Scott, J. M. Penny, W. Van Achterbergh, L. A. Toone, A. J. Ruthven Murray, H. D. Fletcher, J. L. Harris, Col. H. C. B. Hickling 863

Twenty-Ninth General Meeting :

A Note on Mud Flow, by C. C. Wilson 878

Discussion : P. W. Jarvis, G. A. Richards, J. L. Harris, G. H. Scott 880

Reply by C. C. Wilson 883

One Hundred and Fifty-First General Meeting :—

The Modern High-Speed Diesel Engine, and its Place in Road Transport, by W. H. Goddard, A.M.I.Mech.E... 885

Discussion : The President, L. J. Le Mesurier, R. Stansfield, A. J. Wilson, Dr. V. Henny, E. A. Evans, E. R. Redgrove, Major T. R. H. Garrett, A. Lampert, W. B. Rowntree 918

Reply by W. H. Goddard 923

Fifteenth Annual Dinner 925

PAGE

Reviews : " Petroleum Development and Technology, 1933 " ; " Chemical Refining of Petroleum," by VLADIMIR A. KALICHEVSKY and BERT ALLEN STAGNER ; A.S.T.M. Standards on Petroleum Products and Lubricants ; " Symposium on Motor Lubricants " ; " Report on Aerial Survey Operations in Australia During 1932," by W. G. WOOLNOUGH ; " The Viscosity of Pitch," by A. B. MANNING ; " An Investigation of the Accuracy of the Routine Analytical Determinations of Coal and Coke," by H. V. S. BRISCOE 946

One Hundred and Fifty-Second General Meeting :—

Some Notes on the Holley-Mott Continuous Counter-Current Washery as Applied to Petroleum Products, by E. THORNTON, B.Sc., A.I.C. 957

Discussion : THE PRESIDENT, W. C. MITCHELL, Dr. A. E. DUNSTAN, J. E. HACKFORD, Dr. F. H. GARNER, E. S. HILLMAN, Dr. F. SAGER, W. MACNAB 964

Reply by E. THORNTON 968

Trinidad Branch :—

Fourth Annual General Meeting :

Technical Records for Use on an Oilfield, by J. L. HARRIS, M.C., B.Sc., A.R.S.M., A.R.C.Sc. 971

Discussion : H. D. FLETCHER, W. J. C. COOKE, Col. H. C. B. HICKLING, L. A. TOONE, C. E. CAPITO, G. H. SCOTT, C. C. WILSON, L. A. BUSHE, R. N. KIRBY, A. J. RUTHVEN-MURRAY, A. FRANK DABELL .. 1003

Reply by J. L. HARRIS 1013

Twenty-Ninth General Meeting :

Some Notes on the Mixing and Placing of Cement in Oil Wells, by L. A. BUSHE 1017

Discussion : C. E. CAPITO, A. J. RUTHVEN-MURRAY, J. D. FULLERTON, J. W. KNIGHTS, A. H. RICHARD, G. A. RICHARDS, J. L. HARRIS, H. D. FLETCHER, H. W. REID, E. G. ROOKS, J. M. PENNY, A. FRANK DABELL 1024

Reply by L. A. BUSHE.. 1031

Correspondence : " The Analysis of Hydrocarbon Oils " ; " Sedimentary Volcanism " 1035

Reviews : " Kohlenwasserstofföle und Fette " ; " Die Englischen Erdölinteressen in Rumänien " ; " Report of the Fuel Research Board " 1039

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CONTENTS.

	PAGE
Council Officers	i-ii
General Notices	iv-v
Personal Notes and Special Notices	vi-x
New Methods of Dewaxing and Acid Refining Mineral Oils. By Dr. NILS OLOF BACKLUND	1
Integration and Pulsation Errors in Measurement of Quantities of Gas Flowing Through an Orifice. By D. GILMOUR	25
Trinidad Branch: Second Annual Dinner	69
Books Received	72

ABSTRACTS.

		PAGE
Class 100.	Geographic Occurrence	1A
„ 200.	Geology and Origin	6A
„ 300.	Development and Production	8A
„ 400.	Transportation, Storage and Distribution	12A
„ 500.	Properties and Their Determination	15A
„ 600.	Refining and Refineries	25A
„ 700.	Utilisation	35A

AUTHOR INDEX.

The numbers refer to the Abstract Number.

Akin A.-G., 86
Allen, M. C., 35
Anelli, M., 19

Bardeen, J., 22
Barkis, B., 27
Barr, G., 44
Bellingi, A., 19
Blackburn, F., 79
Bohdanowicz, K., 10
Boltus-Goruneanu, M., 50
Bridges, E., 35
Brigham, L. M., 35
Brod, I., 15, 17
Brown, G. G., 61
Brynton, A., 35
Burt, C. E., 35

Carpenter, R. E. H., 61
Church, W. L., 35
Clapp, F. G., 8
Claxton, G., 53
Clemmer, H. F., 100
Collie, B., 42
Copley, E. D., 27
Coward, H. F., 52
Crites, W. J., 31

Danaila, N., 59
Dennis, W. H., 7
Dent, F. J., 76
Dobriansky, A. F., 40
Dryer, G. C., 55
Dunlap, H. L., 58

Edeleanu, L., 69
Edeleanu G.m.b.H., 89
Edgar, G., 49
Edmister, W. C., 29
Egloff, G., 55, 63
Ekstromer, E. C., 35
Embshoff, A. C., 85
Ennis, B., 101
Epley, F. I., 35
Epperson, E. E., 58

Fain, J. M., 60
Fedorov, A., 14
Fenske, M. R., 57
Fulweiler, W. H., 36

Garner, F. H., 50
Gedroitz, N. A., 11
Glenn, J. C., 73
Goodwin, E. T., 2
Greger, F., 103
Guenalt, E. M., 51

Hammer, H. J., 35
Hanseatische Muhlenwerke A.-G., 93
Hartwell, F. J., 52
Hayward, J. T., 30
Heiland, C. A., 23, 24
Hickenbottom, W. J., 46
Hixon, A. W., 60
Hoffert, W. H., 53
Hopkins, G. R., 1
Hutchinson, F. C., 37

Ilyin, S., 16

Jackson, D. H., 60
Jackson, F. B., 35
Jordan, C. W., 36

Kain, W., 70
Kalita, M., 65
Kanter, J. J., 83
Kaumans, J. H., 35
Kent, G. H. L., 3
Keyes, D. B., 62
King, J. G., 78
Knowlton, D. R., 31

Lang, C. E., 35
Lechler, P., 94
Legataki, T. W., 54
Leonhardy, E. C., 63
Leslie, R. W., 101
Lowry, C. D., 55

Maack, H. W., 83
MacLean, A. de, 39
MacQuarrie, J. M., 33
Malcolm, V. T., 82
Mangeldorf, T. A., 43
Marder, M., 98
Martin, A. R., 42
Marx, P. F., 64
Matthews, M. A., 78
Mayo, C. R., 92
McCabe, W. L., 75
McCluer, W. B., 57
McCollum, B., 21
McWilliams, J. R., 34
Meilner, H., 45
Metallgesellschaft A.-G., 86
Migey, A. L., 77
Moeller, J. F. L., 95
Monroe, W. H., 6
Morrell, J. C., 55, 63
Moul, J. R., 74

Nixon, J. D., 35
Nottage, M., 56

Oostveen, W., 91

Pakhamov, S. E., 12
Peters, L. J., 22
Pinkley, G. R., 5
Poole, J. W., 43
Post, E. S., 5
Powers, G. V., 35
Richardson, H. H., 105
Rostovzev, N. N., 17

S.A. Le Carbone, 108
S.A. Mines d'Orbagnoux, 109
Sachanen, A., 67
Sawdon, W. A., 28
Schaarschmidt, A., 98
Sclater, K. C., 26
Shcherbakov, A. V., 13
Simmons, R. P., 35
Snell, F. A., 21
Souders, M., 81
Standard Oil Dev. Co., 90
Standiss, H. R., 35
Stansfield, R., 61
Stone, F., 35
Storch, H. H., 48
Szigeth, G., 96

Tarassov, B., 67
Tauss, J., 45
Thevenaz, W., 47
Thorogood, A. L., 44
Triggs, W. W., 106
Tripiett, J. B., 35
Trouth, J. E., 35
Trusty, A. W., 64
Tyers, F., 107

Van De Gracht, W. A. J. M. van Waterschoot, 9
Vassoyevitch, N. B., 13
Vereinigte Stahlwerke A.-G., 87

Ward, A. L., 36
Weil, J. W., 20
Wheeler, R. V., 51
Williams, R. C., 104
Williams Oil-O-Matic Heating Corpn., 106
Wright, R., 41

Young, A., 4

Zirbel, N. N., 25
Znamensky, W. A., 17

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ABSTRACTS.

Commencing with this issue of the Journal, the Abstracts will be classified in accordance with the scheme adopted by the United States Bureau of Mines in their monthly Bibliography. The complete scheme of this classification is given in Bureau of Mines Bull. 290, Bibliography of Petroleum and Allied Substances, 1922 and 1923, but for the division of the Abstracts only the main headings will be used, as follows:—

Class.	*Subject.*
100	Geographic Occurrence.
200	Geology and Origin.
300	Development and Production.
400	Transportation, Storage and Distribution.
500	Properties and Their Determination.
600	Refining and Refineries.
700	Utilisation.
800	Legislation and Legal Regulations.
900	Miscellaneous.

THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS.

The eighteenth annual meeting of the American Association of Petroleum Geologists will be held at the Rice Hotel, Houston, Texas, March 23–25, 1933.

At the same time and place, the Society of Economic Palæontologists and Mineralogists will hold their seventh annual meeting, and the Society of Petroleum Geophysicists their fourth annual meeting.

WORLD POWER CONFERENCE.

Sectional Meeting, 1933.

The preparatory work of the Organizing Committee of the next World Power Conference, which will take place in 1933 in Scandinavia, proceeds steadily and successfully. The first plenary World Power Conference was held in London in 1924, the next in Berlin, 1930. There have also been Sectional Meetings with concentrated programmes, for instance, at Basel in 1926 and London in 1928. The Scandinavian Conference will be such a special meeting, dealing with the energy problems of large industry and transport.

Participation and collaboration of 15 countries (outside Scandinavia) has been hitherto assured. More than 170 reports have been announced so far. About 1000 persons and organizations have written for information and many of them are already inscribed in the participants' list.

About 40 reports, to be published at the meeting, deal with problems of energy supply in the large-scale industry, such as combined power and heat supply, the role of the large-scale industry in national power schemes, etc. Among these papers some studies suggesting quite new solutions of several important technical and economical problems are contained. In others are presented valuable technical and economical results and experience.

A considerable number of technical papers treat the problems of long distance gas transmission, now particularly prominent in many countries. Other papers are devoted to more special power problems concerning iron and steel industry, pulp and paper, as well as cement, sugar, textile and other steam-heat consuming industries.

Energy questions of transport yield subjects for 62 reports; railway and marine transport, peculiarities of city and suburban traffic are discussed with due emphasis on the keen competition which electritraction and Diesel engines have put up against the steam locomotive.

In face of the difficulties of the world situation, there is more need than ever of rational planning in industry. The good support given the World Power Conference Sectional Meeting in Scandinavia shows that technical and economical circles fully appreciate this opportunity for the man of industry to meet the power expert in order to discuss common problems and exchange experience.

LIBRARY.

The following additions have been made to the Library since December 1, 1932 :—

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—— B.S.S. 472–1932. Mains-Operated Synchronous Clocks.

CANADIAN DEPT. OF MINES. Bull. 731. Feldspar. H. S. Spence.

DIESEL ENGINE USERS ASSOC. Steel Frames for Diesel Engines. C. H. Stevens.

HEILAND, C. A. Preliminary Note on a New Magnetometer. Physics, 1932, 3, 18–22.

—— A Demonstration of the Geologic Possibilities of the Resistivity and Magnetic Prospecting Methods. Terres. Magnetism, 1932, 37, 343–350.

—— and W. E. Pugh. Theory and Experiments Concerning a New Compensated Magnetometer System. A.I.M.E.Tech. Publ. 483.

INSTITUT NATIONAL ROUMAIN. Bull. 30. Canalisation du Secteur des Cataractes du Bas-Danube. II. Barrages-Ecluses-Usines Hydro-electriques. G. C. Vasilesco.

INSTITUTION OF MECHANICAL ENGINEERS. Proceedings. Vol. 122. Jan.–June, 1932.

SCHWARZ, R. Petroleum Vade-mecum. 9th Edn. 2 Vols.

U.S. BUREAU OF MINES. Inf. Circ. 6637. Research Activities in the Mineral Industries of the United States. A. C. Fieldner and A. H. Emery.

—— Rept. Invest. 3198. Survey of Fuel Consumption at Refineries in 1931. G. R. Hopkins.

—— Tech. Paper 521. Oil Prospecting in Kentucky by Resistivity Methods. J. H. Swarty.

U.S. BUREAU OF STANDARDS. Misc. Publ. 138. Annual Report of Director for the Year Ended June 30, 1932.

U.S. GEOLOGICAL SURVEY. Bull. 831-B. The Ashland Coal Field, Rosebud, Powder River, and Custer Counties, Montana. N. W. Bass.

—— Bull. 835. Geology and Oil Resources of the Elk Hills, California. W P. Woodring, P. V. Roundy and H. R. Farnsworth.

—— Bull. 836-E. The Tatonduk-Nation District, Alaska. J. B. Mertie.

—— Bull. 837. Tertiary and Quaternary Geology of the Lower Rio Grande Region, Texas. A. C. Trowbridge.

—— Prof. Paper 166. Physiography and Quaternary Geology of the San Juan Mountains, Colorado. W. W. Atwood and K. F. Mather.

—— Prof. Paper. 167. Lower Triassic Ammonoids of North America. J. P. Smith.

—— Prof. Paper 171. Geology and Ore Deposits of the Pioche District, Nevada. L. G. Westgate and A. Knopf.

—— Prof. Paper 173. Geology and Ore Deposits of the Stockton and Fairfield Quadrangles, Utah. J. Gilluly.

—— Prof. Paper 174. Physiography and Glacial Geology of Eastern Montana and Adjacent Areas. W. C. Alden.
—— Report of Director for Year Ended June 30, 1932.
WILKINSON, F., and F. J. FORTY. Bituminous Emulsions for Use in Road Works.

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THE INSTITUTION OF PETROLEUM TECHNOLOGISTS.

THE ONE HUNDRED AND FORTY-SIXTH GENERAL MEETING of the Institution was held at the Royal Society of Arts, John Street, London, W.C. 2, on Tuesday, December 13th, 1932, Mr. T. DEWHURST, Vice-President, occupying the Chair.

The Chairman, in opening the meeting, said that the President was unavoidably absent and had asked him to acquaint members with the fact that an independent body was arranging to hold an International Petroleum Exhibition at the Agricultural Hall in July next, and that the Council of the Institution, wishing to take advantage of the occasion, had appointed a committee to discuss ways and means of holding therewith a World Petroleum Congress. This announcement, he said, was merely a first intimation, and he expected that the President would give members further particulars in due course.

The Secretary read the names of the candidates nominated for election, and the following list of members elected :—

As Members.—Francis Rodwell Banks, John Henry Cullinane, Carleton Ellis, William Harry Marcus Higham, Poul Gregers Jensen, Hans G. Kugler George Robert Nixon, Malcolm John Robertson, Tom Sparshott.

As Transfer to Members.—John Berridge Kay, Alexander Thomas Spencer, Simpson.

As Associate Members.—Cyril Blake-Smith, William Vincent Burggy, Albert Edward Chrisman, William Allen Hedworth, Henry Ernest King, John Wilfred Knights, Arthur Osborn, Krysfeldt Pedersen, William Wallace Reed, Leonard Stephen Barrington Simeon, Ziro Tuzi, John Hopwood Varley.

As Transfer to Associate Members.—William Edwin John Broom, Samuel Elliman, John Stanislaus Gaynor, George Camille Felix Greant, Norman George Gullick, Archie Ronald Javes, Patrick Nixon Dick Porter.

As Students.—Richard Chandler, Brian Downward, George Douglas Chamberlin Dunmore.

As Associate.—Harold Clarkson Huggins.

New Methods of Dewaxing and Acid Refining Mineral Oils.

By Dr. NILS OLOF BACKLUND.

DEWAXING.

AT the Congress of Polish Petroleum Technologists in December, 1930, new method of dewaxing was for the first time brought to public knowledge. The figures and information given at that occasion were mainly based on tests with Polish oils from Schodnica and Urycz.

These tests proved that automobile and cylinder oils with pour point below 0° C. could be produced without difficulty from the

crudes in question. The tests were only carried out on a small scale, however, viz., with up to 150 gallons of mixture, *i.e.*, at favourable mixing proportions about 90 gallons of oil. The hourly capacity of the test centrifuge was up to 55 gallons of mixture, corresponding to about 33 gallons of oil.

This test plant was too small to permit reliable conclusions to be drawn with regard to commercial scale operation, and for this reason a larger centrifugal separator was built, having an hourly capacity of up to 265 gallons of mixture ("capacity" means here the quantity that can be satisfactorily treated per hour).

The chilling and crystallizing equipment available was so small, however, that the large separator could be continuously run for only 30-45 minutes. Moreover, the temperature of the mixture could only occasionally be brought below $-11°$ F.; on an average the tests were carried out at a separating temperature of -4 to $-7°$ F. Nevertheless, the tests permitted the performance of the two sizes of separators to be compared and indicated the principles on which the results obtained with the small separator could be applied on the results to be expected with the large one.

With regard to the above-mentioned oils it should be observed that the highly viscous lubricating oils (automobile and cylinder oils) produced from these crudes could not be dewaxed in the plants existing in Poland. Due to this fact the rich oil fields producing these crudes were at that time only comparatively little exploited.

Seeing that the latest distillation processes, for direct production of highly viscous oils (distillates or residues), were at that time rapidly gaining ground, the dewaxing tests were adapted to this progress of distillation technics, and were thus extended also to Pipe-Still distillates. The results obtained rendered it possible to introduce on the market the new large dewaxing separator, intended for commercial scale plants.

Before the dewaxing results obtained in practice are further described it may be permitted to give a brief description of the process itself.

It is well-known that up to the present only one method of dewaxing by means of centrifugal separators has been employed in the mineral oil industry, viz., the American Sharples method, using benzine as solvent and thus separating the wax from the oil, after previous cooling, as the heavier component. This method is sufficiently known in theory and practice to render further elaboration superfluous.

Since the benzine method has several disadvantages, however, and can by no means solve all dewaxing problems, *the question of a suitable solvent* was carefully investigated, and considerable research work in this direction was carried out.

The first requirement on a solvent for this purpose is that the specific gravity of the oil solution, in which the wax precipitates during cooling, differs from that of the wax—otherwise a centrifugal separation is, of course, impossible.

Solvents having either a lower or a higher specific gravity than the wax can be employed—the greater the difference the better, since a smaller amount of solvent will then be required. The solvent should dissolve the oil in any proportion and at any temperature, it must not solidify at the cooling temperature in question and it should have such low a boiling point that it can be completely distilled off from the oil and wax without any difficulty.

As specific *lighter* solvent practically only benzine can be considered, although the specific gravity is not very favourable, seeing that the use of a very light benzine would result in excessive evaporation losses and fire hazard. One thus has to use a comparatively heavy benzine and add a correspondingly larger quantity, which means larger crystallizers and separator plant as well as more refrigerating work.

The large proportion of solvent required is detrimental also to the final result of the dewaxing, because benzine retains, even at very low temperature, a certain amount of dissolved wax, which thus remains in the oil-benzine blend after the centrifugal separation. When distilling off the benzine this wax remains in the oil, increasing its pour point.

It should be noted that many grades of benzine having a high naphthenic or aromatic content have such a high specific gravity that they are unsuitable for use as solvents in the dewaxing process.

When looking for suitable solvents to replace benzine only such solvents, which are *heavier* than the heaviest wax were considered. The chlorinated hydrocarbons, carbon tetrachloride, etc., seemed to be particularly suitable in view of their non-inflammability, seeing that much damage has been caused by unexplainable and thus unavoidable fires in benzine dewaxing plants. Also the high specific gravity and low boiling point of these solvents rendered them very suitable for the purpose in question.

The fact that by using a heavy solvent the wax is obtained, at the centrifugal separation, as the specific lighter component and will thus have to be discharged from the central part of the centrifugal bowl was also considered as a great advantage, since it is much easier to effect a continuous discharge of the solid wax in that way.

Another advantage of using a specific heavy solvent is the possibility of having a protecting layer of water floating on the top of the solvent in the storage tanks, thus greatly reducing the losses of solvent due to evaporation.

Of the solvents in question trichlorethylene ("tri") has proved particularly advantageous due to its low specific heat and latent heat of vaporisation heat. *The physical properties of tri* as compared with those of benzine are as follows:—

Solvent.	Specific gravity.	Boiling point.	Specific heat, B.Th.U./lbs.	Latent heat, B.Th.U./lbs.
Trichlorethylene	1·47	188° F.	0·23	102
Benzine ..	0·67	About 188°F. (final distilling point).	0·45	130

Since tri contains chemically bound chlorine, there is a theoretical possibility of formation of hydrochloric acid, which rendered certain preliminary investigations necessary. A liberation of chlorine takes place under the influence of light and at increased temperature, but this temperature is not attained when distilling off the tri from the oil and wax.

By continuously redistilling a certain quantity of tri for months and months with steam of 224-226° F. any liberation of chlorine or formation of hydrochloric acid could not be effected. Manufacturers of tri (*e.g.*, dr. Alexander Wacker in Munich) confirm this fact, and users of tri, *e.g.*, in U.S.A., have had the same experience (compare also *Ind. Eng. Chem.*, 1932, **24**, 1164-1168).

The fact that the formation of hydrochloric acid at a high temperature (above about 250° F.) takes place at a very slow rate and in negligible quantities has been proved by experience during tests lasting for several years. During this period trichlorethylene was repeatedly distilled off from oil in a boiler with a tube condenser, containing about 130 lb. of oil-tri mixture. The quantity of tri thus distilled off amounted to about 4400 gallons (64,500 lb.), and the distillation was effected by direct fire, enabling the temperature to be increased to 465° F. at the end of the operation. Even after this long period of distilling no corrosion worth mentioning could be observed.

Any extensive investigations regarding the insolubility of wax in tri at different temperatures have not been necessary, since the first tests proved that tri meets all requirements in this respect.

It was also established during the first tests that the mixing proportions of oil and tri could be varied between wide limits, the paraffin content and viscosity of the oil determining the quantity of solvent to be added.

The proportions of oil and tri vary between 65-45 parts of oil to 35-55 parts of tri by volume. The average proportions, however,

of oil: tri are 55-50 and 45-50 by volume. Increasing paraffin content of the oil requires a greater increase of the quantity of tri than does increasing viscosity of the oil.

These figures show that at the dewaxing of a certain quantity of oil the volume of the mixture of oil and solvent is always much smaller than with the benzine method. The latter requires a dilution of 35-20 parts of oil, 65-80 parts of benzine, by volume.

The experience made with regard to the *rate and degree of cooling* of the oil-tri mixture is of the utmost interest and importance.

After a few tests it was established that an appropriate size of the precipitated wax-crystals was obtained at comparatively rapid cooling, viz., in only 12-18 hours.

Just as the paraffin content determines the suitable quantity of solvent, it determines also the suitable rate of cooling, viz., the more paraffin, the more slowly has the cooling to be carried out. More than 18 hours cooling is, however, never required. Most oils which have been tested need only 12 hours, some of them 15, and only very few 18 hours cooling (whereas with the benzine method 48-72 hours are usually required).

The rate of cooling should not be constant all the time. It has been found that it is advantageous to carry out the cooling down to 32° F. at a slower rate than the subsequent cooling down to the desired temperature. During numerous dewaxing tests in U.S.A. the mixture was generally cooled at a rate of 9° F. per hour down to 32° F., and at a rate of 14° F. per hour from 32° F. down to about −22° F.

It is difficult to give any general rules with regard to the degree of cooling. As is the case with the proportions of tri and oil, the cooling temperature has to be adapted to each particular oil, since the difference between the lowest cooling temparature and the pour point of the dewaxed oil varies considerably with different oils, viz., from 0 to 40° F. according to test results hitherto obtained.

The following table shows this interesting *relation between cooling temperature and pour point* obtained with various oils :—

Oil.	Viscosity Secs. Redwood.	Pour point °F.	Proportions oil : tri (by volume).	Cooling temp. °F.	Pour point of dewaxed oil, °F.	Difference between cooling temp. and pour point, °F
Residue ..	187 at 122° F.	25	60 : 40	−2·2	−2·2	0
Distillate ..	365 at 122° F.	39	60 : 40	−6	5	11
Distillate ..	105 at 212° F.	32	50 : 50	0	12	12
Red. press oil	345 at 122° F.	32	60 : 40	−6	12	18
Distillate ..	105 at 212° F.	32	55 : 45	0	19	19
„ ..	90 at 212° F.	97	50 : 50	−4	18	22
„ ..	105 at 212° F.	32	50 : 50	−22	7	29
„ ..	120 at 212° F.	95	40 : 60	−15	19	34
„ ..	108 at 212° F.	95	40 : 60	−22	18	40

It has further been found that *the cloud point* of most oils dewaxed on the tri-method is very close to the pour point, and that in most cases the difference is not more than 2–3° F.

With some Polish oils the interesting fact was observed that the dewaxed oil solidified without any previous clouding at all. Even a further deep-cooling did not effect any clouding of the oil.

The smaller quantity of solvent to be added, the considerably shorter period of cooling and, in many cases, the possibility to work at higher temperatures are advantages of great importance when comparing the tri-method with the benzine method from an economical point of view.

It has been found that the capacity and power consumption of the refrigerating plant required is only about one-third to one-half with the tri-method as compared with the benzine method, and the first cost and operating cost are thus correspondingly lower.

As far as hitherto could be ascertained, the new process is rather insensible to possible variations in the conditions at the distilling and fractionating of the paraffinous crude oil, whereas with the benzine method the presence of only small quantities of pyro-paraffin (macrocrystalline) is sufficient to render a continuous discharge of the separated wax from the centrifuge impossible.

The paraffin oil fraction which is intended for direct treatment in filter presses and is normally called " paraffin oil " (or its concentrates after dewaxing in filter presses) cannot be dewaxed in practice by means of the benzine method, even if this should be of advantage from an economical point of view.

With the tri-method concentrates of press oil have been continuously dewaxed. For instance, a press oil concentrate having a specific gravity of 0·930, viscosity 22·7 secs. R. at 122° F., pour point 23° F., from Boryslaw crude, after refining showed an increased pour point of 34° F. This oil was dewaxed prior to refining at a dilution of 60 : 40 and a temperature of −4° F., an oil with pour point 10° F. being obtained. After refining the pour point was as low as 16° F., and the tri-dewaxing had thus improved it by not less than 18° F.

A refined oil being finished with Fuller's earth and having a viscosity of 190 secs. R. at 122° F. and a pour point of 34° F. (press oil concentrate from Boryslaw crude) was likewise dewaxed at a dilution of 60 : 40 and a temperature of −4° F. A pour point of 18° F. was obtained, corresponding to an improvement of 16° F.

The tests were at last extended also to such oils which could not be satisfactorily dewaxed in filter presses or with the benzine method. The results obtained with a cylinder oil distillate from Columbian crude are particularly interesting.

This oil (100 secs. R. at 212° F., pour point 32° F.) should be

dewaxed to 21° F. pour point. The tests were carried out in a large American Research Institute, in which extensive experiments with the benzine method had already been made. With this method the low paraffin content of the oil in question proved to be of considerable disadvantage from a technical and economical point of view. (Whether also oils of other origin offer the same difficulties cannot yet be stated.)

It was necessary, with the benzine method, to work at the usual high dilution and low cooling, but nevertheless the yield of dewaxed oil showed a very unfavourable relation to the original content of paraffin. This latter drawback could, however, be eliminated to a certain extent by adding some petrolatum to the oil prior to dissolving it in benzine. In this way an oil with pour point 21° F. could be obtained after cooling down to −30° F., the yield of oil being 96 per cent.

With due consideration to these results the oil in question was dewaxed on the tri-method at a dilution of oil : tri = 50 : 50 (by volume) and a temperature of −25° F. At a yield of 95 to 95·5 per cent., an oil with pour point 1 to 3° F. was obtained, and at a yield of 96·5–97·3 per cent. the pour point was about 7° F. Further tests at the same dilution gave the following results :—

at −6° F.	97–97·8% yield	pour point 10° F.
at 0° F.	98% yield	pour point 12 to 14° F.

At the following tests the dilution was reduced to 55 per cent oil : 45 per cent. tri. The results were then :—

at −6° F.	98% yield	pour point about 18° F.
at 0° F.	98·2% yield	pour point about 19° F.

The tri-method thus enabled the separating temperature to be raised from −30° F. to 0° F., and the yield of dewaxed oil to be increased from 96 to 98%. The quantity of oil dewaxed per separator in 24 hours was 110 to 116 barrels, with the tri-method against only 38 to 40 barrels with the benzine method.

The dewaxed oil was bleached to a light yellow colour (about Robinson 5) by means of percolation through Fuller's earth. This treatment had no influence on the pour point of the oil which remained at the above-mentioned low figure.

It was also observed that the cloud point of the oils in question was only about 1–2° F. above the pour point. When dewaxed on the benzine method the oils had a cloud point about 9 to 15° F. above the pour point.

Comparative tests were also carried out with a cylinder oil distillate, 110 secs. R. at 212° F., pour point 95° F. Part of the oil had been treated with sulphuric acid and Fuller's earth, and

another part with sulphuric acid *only*. The latter oil could not be continuously dewaxed with the benzine method.

These tests also gave very interesting results. Due to the high paraffin content (about 12 per cent.) the tests had to be carried out at a higher degree of dilution than the previous ones. The dilution was, however, the same with both kinds of oil.

Oil.	Dilution.	Temperature.	Pour Point.	% Yield.	Barrels dewaxed oil per 24 hrs.
I. Treated with Fuller's earth ..	40 : 60	—24° F.	17 to 21° F.	87·5	50
II. Not treated with Fuller's earth ..	40 : 60	—24° F.	12 to 14° F.	86·6	60
	40 : 60	—20° F.	12° F.	86·6	58
	40 : 60	—15° F.	19° F.	88·8	50

From these figures will be seen that to attain the same pour point of the oils No. I. and No. II., at the same hourly capacity oil No. II. (which had *not* been treated with Fuller's earth) needed 9° F. less cooling and still gave 1 per cent. higher yield of dewaxed oil.

With the benzine method the capacity per centrifuge in 24 hours when treating oil No. I. to the same pour point was 38-40 barrels, at a yield of 87·7 per cent.

The "filter yield," *i.e.*, the quantity of oil which can be brought to the desired colour with a certain quantity of Fuller's earth, proved to be somewhat higher with oil No. II. than with oil No. I.

Several samples of the dewaxed oil No. II. were bleached to about 4·8 Robinson by means of percolation, whereafter the pour points were once more determined. In two cases the pour point had been increased by 2° F., in all other cases it had remained constant.

The fact that the oil which had not been treated with Fuller's earth could not be continuously dewaxed by the benzine method is probably due to the same circumstances which render it impossible to dewax, with this method, an *asphaltic residue* without previous refining.

When the oil contains asphaltic matters these are partly precipitated by the benzine added and thrown out against the periphery of the centrifugal bowl, where they prevent the wax from being continuously discharged. On the other hand, part of the asphalt bodies remain in colloidal solution in the oil and impair the precipitation of the wax, thus acting as so-called "inhibitor."

The tri-method is entirely different in this respect since tri does not cause any precipitation of free asphalt but, on the contrary, dissolves asphalt. Observations seem to indicate that the asphalts present in the oil in a colloidal state are transferred into complex solutions, thereby losing their character as "inhibitors."

Residual oils in an advanced state of carbon-formation can also

be continuously dewaxed with the tri-method. Experience has shown that coky matters, being insoluble in tri and having a specific gravity close to that of the oil-tri-component, are continuously discharged with the latter from the centrifugal bowl.

Regarding the paraffin or petrolatum obtained during the dewaxing there is not much to be said. It is to be considered as a by-product and is in most cases redistilled to pressable wax.

The oil content and melting point of the deoiled wax or petrolatum depend on the requirements on the dewaxed oil. The design of the dewaxing separator permits a continuous discharge, without any special means such as hot water, etc., also of paraffins having a comparatively high melting point. The hardest paraffin which has been continuously obtained during tests had a melting point of 141° F. after the tri had been distilled off.

Regarding the separator, it may be mentioned that its design differs considerably from that of the usual types of centrifugal separators, owing to the new, special requirements which it has to fulfil. It is completely vapour tight, works at a speed of 9000 r.p.m. and, being once adjusted to give the desired purity of the dewaxed oil, it requires practically no further attention.

The maximum capacity obtained during the tests was 116 barrels of dewaxed (tri-free) oil in 24 hours of continuous operation, corresponding to about 265 gallons of oil-tri-blend per hour. The average capacity is about 200-220 gallons of mixture per hour, or 50-100 barrels of oil in 24 hours, depending on the wax content and viscosity of the oil to be treated and the pour point required of the dewaxed oil.

Acid Refining.

In regard to the *acid treatment* of petroleum products it should be noted that, in spite of the remarkable progress achieved during the last years in nearly all branches of the petroleum industry, this process has not yet reached an entirely satisfactory stage.

While it was possible to make processes like distillation, dewaxing and cracking to work continuously, the acid treatment still remains in the old discontinuous stage and, consequently, still suffers from all the disadvantages thereof.

The procedure of acid treatment being sufficiently known, it may be permitted to give only a short survey of those points which would render a modernisation particularly desirable.

The construction of the present equipment for acid treatment is governed by the fact that separation is effected by gravity settling only. This phrase of the process may last for twenty-four hours or, with heavy oils, even several days. A continuous operation is, therefore, not possible and the refiner is compelled to choose for the whole procedure correspondingly large vessels. This has directly and indirectly several disadvantages.

It is, first of all, very difficult to provide for a sufficiently effective mixing, as the use of efficient mechanical mixers for such huge quantities offers mechanical difficulties. Refiners, therefore, have chosen the method of air blowing which, superficially viewed, represents a simple solution. As a matter of fact, however, the degree of mixing is bad and the method involves new disadvantages.

First of all, the humidity of the air has a diluting effect on the sulphuric acid, and secondly, the oxygen present in the air has an oxidising effect of its own on the oil. It may be that this process of oxidation is favoured by the acid sludge formed during treating. Both these troubles become more and more serious with increasing temperature, as is well known to every refiner.

It is easy to understand that with the great quantities to be treated with each batch, an even distribution of the acid in the oil cannot be instantaneously effected, even with intensive mixing. The mixing period with compressed air must, therefore, be extended which in turn increases the detrimental influence of the air.

Considered purely superficially, the intimate contact of acid and oil results in the formation of acid sludge. When working in conventional agitators the acid does not at first reach the required degree of dispersion, and is to a great extent occluded in the tar which is formed immediately after the contact of some acid with the oil. Part of the acid is thus at first excluded from the treating process. The air mixing must be continued for some time in order to disintegrate the tar formed and to make at least a part of the occluded acid effective for the reaction. The reactivity of this acid has in the meantime suffered a dilution with moisture from the air.

In all tars withdrawn after settling a considerable quantity of free acid could always be detected. This acid has consequently been lost for the treating process. Dr. Kronasser has proved by microscopical and analytical investigations that acid sludge formed after effective mechanical mixing always contains much less free acid than the tar or sludge formed during the batch process with air mixing.

The slow settling of the sludge is a further serious disadvantage, since the treated oil is all the time in contact with the finely divided acid sludge. With most oils it seems as if part of the coloured components of the sludge would go into solution in the oil. In any case an oil from which the acid sludge has been quickly removed always shows a better colour than if the sludge has settled out slowly. A rapid and complete separation of oil and sludge is not possible when working with conventional agitators.

Investigations have shown that from a settled machine oil, ready for neutralisation, 0·6 per cent. of tar could be separated by use of a centrifugal separator. For cylinder oils the corresponding

figure was around 2·5 per cent. It is interesting to note that in practice these figures have proved to be more or less constant. Even after further washing of the oil, acid sludge particles always remain therein.

The acidity gives a good indication of the purity of a settled oil. Properly settled oils show a low acidity which is always much higher, however, than in the case of centrifuged oils.

A high acidity renders the neutralisation more difficult, since on one hand a greater amount of chemicals is necessary, and on the other hand emulsification is possible. In both cases the refiner has to confront with higher oil losses. Finally, when drawing off the acid sludge from the bottom of the settling tank (agitator), some oil is unavoidably carried away. This fact, too, is responsible for a not unimportant increase of the refining losses.

It was a logical move to introduce centrifugal force to replace the gravity settling and thus to overcome all the above-mentioned troubles. Experiments in this direction had been made already at an early date but without any success at that time. Only after the advance of the centrifugal separator technics and the research work of the Separator-Nobel Company during the last five years was it possible to develop an apparatus which effects a continuous, instantaneous separation of the mixture into tar-free oil and oil-free tar.

With this separator available there is no longer any reason for adding the acid to a large volume of oil and then trying to disperse it by mixing. Instead, exactly proportioned quantities of oil and acid are now continuously fed into a highly efficient mechanical mixer at a rate corresponding to the suitable throughput of the separator. The intimate mixture of oil and acid is then passed into a reaction vessel, where it remains for an appropriate time (from a few minutes up to one hour, depending on the oil) before being fed to the separator. Along those lines the continuous refining process was developed, the basic principles thereof being :—

1. Maximum utilisation of added sulphuric acid by disperse and equal distribution in the oil ;
2. Exclusion of air during the whole procedure of acid treatment ;
3. Shortest possible contact time between oil and acid sludge ;
4. An oil free from sludge particles and a sludge free from oil is obtained.

Point one is satisfied by introducing proportioned quantities of oil and acid into a highly efficient mixing apparatus, the reaction mixture leaving this apparatus a few seconds later. This mixture is then passed into a closed reaction vessel, which is of such dimensions as to allow the mixture to remain there as long as necessary

for the optimal reaction time. By this procedure the second point (exclusion of air) is also satisfied.

The third and the fourth requirements are simultaneously fulfilled by means of this separator. The mixture coming from the reaction vessel is at once completely separated into acid sludge and oil, thus definitely excluding the objectionable influence of the sludge on the treated oil.

In this operation three liquids of different specific weight must be continuously separated and discharged from the separator. As previously stated, the sludge always contains varying quantities of sulphuric acid. Due to the great centrifugal force generated in the separator bowl acid is liberated from the sludge. Since standard separators are designed to discharge continuously only two components, they cannot be used for our purpose. Only after the continuous discharge of the third component was made possible, one could speak of a *continuous* acid-treating process with the aid of centrifugal separators.

In the case of the acid sludge separator this was achieved by the introduction of a "viscosity capillary." By aid of this capillary the continuous separation is taking place as follows: the free acid, as the heaviest component, is withdrawn from the periphery of the bowl through the above-mentioned capillary, and the other two components, sludge and oil, are discharged each for itself in the usual way.

The acid sludge, which in many cases is very viscous, passes through the bowl and is discharged without any troubles.

The experiments were first carried out with vertical mixers with effective stirrer. These mixing vessels served at the same time as reaction vessels, their dimensions being chosen so as to give the desired reaction time. For oils which required a long reaction time the mixing vessel had to be very large and a great quantity of liquid had to be kept in motion. As this required too much power the mixer was separated from the reaction vessel.

This new method gave a far better mixing effect at a considerably reduced power consumption. Centrifugal pumps proved to be highly efficient mixers. Oil and acid meet in the suction line of the over-dimensioned pump, where the components are subjected to an intense mixing, only to be separated again after the reaction is completed.

It has been sufficiently proved in practice that, in view of the further treatment, the acid-treated oil should be as clean as possible. No matter by which method the neutralisation is carried out, the difference between settled oil and centrifuged oil is striking.

In the course of the caustic wash it could be easily observed that the separation of caustic solution and oil takes place much more quickly with a centrifuged oil. Thus, time and wash water are

saved. Due to reduced washing, the losses of oil are also reduced. Moreover, the possibility of formation of emulsion is much smaller in the case of centrifuged oil. It could further be ascertained that the acidity of the acid-treated and centrifuged oil is so low, that it is possible to treat it directly with fuller's earth. Considerably less earth is required than in the case of settled oil, which naturally means a higher yield of finished oil.

Another advantage which should not be overlooked is the possibility to carry out the acid treatment at higher temperatures without impairing the colour of the finished oil. At increased temperature the sulphuric acid is much better utilised and a smaller amount is consequently required.

Briefly summarised, with the apparatus described it is possible to do away with the disadvantages of the old method. The exactly proportioned quantity of acid is instantaneously dispersed in the oil, and the reaction time is closely controlled by proper adjustment of the reaction vessel, the separation of oil, sludge and free acid takes place instantaneously in the separator, oil-free sludge and sludge-free oil being obtained. The whole process is a continuous one and the air is excluded. The process can easily be controlled in every phase and the desired temperatures be maintained.

Comparing the new process with the old one, the following advantages will at once be realised :—

1. The quantity of acid not taking part in the reaction is reduced. Consequently, an economy in acid and a higher yield of finished oil is obtained.
2. The separation of oil and sludge is very sharp and the oil which is otherwise lost with the sludge is thus saved.
3. The pepper sludge remaining in a settled oil is removed by the separator, together with the main portion of the sludge. This gives the oil a lower acidity and, consequently, involves a reduction of the consumption of neutralising agent.
4. The smaller consumption of neutralising agent reduces the oil losses.
5. The process being entirely mechanical and automatic is easily controllable.
6. The detrimental influence of too long a heating and reaction period is eliminated.
7. It is possible to work at higher temperatures.
8. The process plant requires only little space, which means economy due to the elimination of huge agitators.

It is not possible to give in advance detailed directions for the treatment of a certain oil. By preliminary experiments, however, the best method can easily be determined. This subject has been very completely treated by Weir, Houghton and Majewski in

their paper, "The Acid Treatment of Lubricating Distillates" (*Ind. Eng. Chem.*, vol. 22, Dec., 1930, 22, 1293-1300).

Of continuous acid refining tests recently carried out on a large scale, those made with Rumanian asphaltic-base, vacuum pipe still distillates are of particular interest. The consumption of acid was in that case very considerably reduced and the efficient mechanical mixing allowed for a total reaction time of 2 to 4 minutes only. In the following a comparison between the old and the new method is given :—

	% Acid used.	React. time.	Colour/ Union.
Spindle oil, 230 secs. R: at 68° F.—			
Discontinuous treatment	3·0	6 hrs.	1·5—2
Continuous treatment	1·5	1·5 min.	1·5—2
Machine oil, 154 secs. R. at 122° F.—			
Discontinuous treatment	2·4	24 hrs.	3·5
Continuous treatment	1·8	2 min.	2·0—2·5
Machine oil, 770 secs. R. at 122° F.—			
Discontinuous treatment	2·6	26 hrs.	6·0
Continuous treatment	2·24	2 min.	4—4·5

It may be of interest to mention here some results obtained in a certain refinery in Northern Europe, where all lubricating oils (mainly distillates of South American crudes) are treated in a continuous refining plant. According to information received from that refinery, it had been possible to reduce the acid consumption for spindle oils from 4 to 2 per cent. by weight. For machine oils, 406 secs. R at 122° F., the consumption of acid was reduced from 7 to 5 per cent. by weight. At the same time the yield of oil was increased from 92 to 94 per cent.

Information from the same source also showed that the neutralisation could be carried out much more quickly and easily and that a considerable reduction in the consumption of fuller's earth was effected.

What has been said regarding the continuous treatment of lubricating oils also holds true to a large extent to the refining of cracked gasoline. Particularly the demand for good anti-knock properties—so much increased recently—makes it imperative to keep the time of reaction within very narrow limits, just as is the case with lubricating oil.

It is possible to obtain good anti-knock properties—or high octane numbers—by treatment either at low temperature or at normal temperature and shortest possible reaction time. Investigations carried out in U.S.A. with the process showed that reaction times from only a few seconds up to 15 seconds were sufficient for a proper acid treatment of gasoline without any considerable reduction of the octane number. A treated pressure distillate gives now, in commercial production, octane number 70, against only 50 with the old method. The gum tests of the present and the old product show the relation 5 : 9, *i.e.*, a considerable improvement.

This might be due to reduced formation of peroxides as a direct consequence of the shorter contact time.

By the short and closely controlled contact time not only the oxidation, but also the polymerisation is reduced to a minimum. Therefore, in many cases redistillation can be omitted, but where necessary a higher yield of a lower end point distillate will result.

Between gasoline and lubricating oil there is the wide field of kerosines, and naturally the question arises as to whether it is not possible to refine also these products continuously from beginning to end. Investigations have been carried out, but not yet on a commercial scale. The question is of greatest interest, and the results of the preliminary experiments were such as to demand continuation of this work.

A kerosine treated in a refinery by addition of two subsequent portions of acid could, when continuously mixed and separated in an efficient equipment, be treated by one portion only and still gave a perfect product. The acid consumption could be reduced by 17–22 per cent. The kerosine was entirely odourless, and the colour (Stammer) was improved from 200 to 300.

The optimum reaction time for that particular kerosine was 5 minutes, with a tolerance of 1 minute. More or less gave immediately inferior results.

The acidity of the centrifuged kerosine was very low, which enabled the neutralisation to be carried out without preliminary water washing.

The continuous method was employed also for the neutralisation. Even after very intensive mixing with 2 per cent. of a 6° Bé. soda solution, a complete separation of the two components could easily be effected in the centrifuge, and afterwards one waterwash only —with intense mixing—and separation gave a neutral, finished product, ready for shipment.

These applications of the continuous refining process—for pressure distillate and kerosine—offer many possibilities of interest, although the main importance and advantages of the process are to be found in the field of lubricating oil refining where it is destined to effect a revolutionary economy in production costs.

DISCUSSION.

The Chairman said that the meeting would agree that the paper had been very valuable and interesting. He understood that the two processes advanced were now well established on a commercial scale, although on reading the paper he had received the impression that they were only now emerging from the experimental stage. To the layman it seemed rather surprising that the paper should contain little or nothing on the important subject of costs. In attempting to demonstrate the superiority of the methods

advanced, the author might have been expected to make a comparison of actual or estimated costs.

Mr. J. McConnell Sanders said that by the use of the phrase "new methods" one naturally asked the question whether the process was an entirely revolutionary and novel method of refining.

He did not think the present process was entirely new to any practical refiners who were present. Petroleum technologists had known and used centrifugal methods for dewaxing purposes for many years past, and the outstanding improvement in the process described by Dr. Backlund was the use of a heavy, fireproof solvent which obviated the use of a third liquid as a carrier and allowed the wax to be taken off continuously from the centre of the bowl.

The particular improvements introduced by the method should mean a great deal in economical working. The use of this heavy solvent meant, as the paper had shown, that a smaller volume could be used in proportion to the oil; in other words, the concentration of wax in the lighter effluent was relatively greater. The author, however, had not touched upon the fact that the solvent which he used was twice as heavy as the benzine used in the old Sharples process; therefore, dealing only with the power consumption to rotate the centrifuges, one wondered whether the effect of the greater weight of liquid involved for equal volumes processed might not to some extent neutralise the economy effected.

Another point of great interest was the approximation of the pour and cloud points. This would interest especially many members who had to deal with crudes which yielded wax which was crystallisable only with difficulty. Dr. Backlund had suggested as an explanation that there might be something in the oil which was more readily soluble in the new solvent trichlorethylene, and the removal of this substance enabled the wax to assume a different physical state when separating than it did when using benzine. He would like the author to give a fuller scientific explanation of this phenomenon.

Turning to the acid treatment by centrifugal methods, the speaker supposed that all members knew that continuous treatment was by no means novel. Centrifugal treatment by centrifugal pumps was well known, and members would recall the many difficulties which had been encountered from a mechanical point of view in maintaining such pumps in service, difficulties arising mainly from corrosion and erosion, especially with certain types of sludge acid. He asked the lecturer to tell them something about the construction and design of the centrifuges which he used, especially as regards the more important bearings and the material of which they were made. At first sight it would appear, the speaker commented, that these centrifugal separators would need

as much, if not more, expenditure in maintenance than the ordinary acid-resisting centrifugal pumps.

Dr. F. B. Thole said that it was generally agreed that the older methods of acid treatment, which usually implied inefficient contact for a prolonged time, had no advantages and many disadvantages as compared with a process which gave rapid and intimate contact with the correct quantity of acid followed by immediate and thorough separation. The principal difficulties were those mentioned by Mr. McConnell Sanders, namely, chemical and mechanical wear and tear on the mixing and centrifuging plant.

The section of the paper dealing with dewaxing raised many points of interest which would no doubt be discussed by those present whose daily work was concerned with this operation. It was well known that in distilling many petroleums two waxy fractions were obtained, the first containing large wax crystals which could be easily removed by filter pressing, but were difficult to centrifuge, and the second containing very small, needle-shaped wax crystals (the so-called "amorphous distillate") which could not be dewaxed by filtration and required dilution and centrifuging. In view of the statement that the "tri" process was rather insensitive to possible variations in the conditions of distilling and fractionating the oil, he would like to ask if the use of trichlorethylene altered the crystalline nature of the wax in these respective fractions and so made it more amenable to separation than was the case in corresponding benzine mixtures.

In view, also, of the fact that the difference between the cooling temperature and the pour point of the resultant oil varied greatly with different distillates, he would like to ask if this depended on whether the oil were of the naphthenic or paraffinoid class, whether the oil was of low or high viscosity, or whether the wax content was high or low.

Lieut.-Colonel S. J. M. Auld said that he was inclined to dismiss the acid treatment portion first of all as being much the less important. Continuous methods of acid treatment of different kinds were well enough known, and it was not a far cry to their combination with centrifugal methods of separating the acids and the sludge. Such processes had indeed already been used. He asked whether it was quite certain that the older methods of acid treating, especially of lubricating oils, by successive small quantities of acid had been sufficiently considered. He supposed that it was generally regarded as proven that whatever method was adopted to bring the oil and the acid in contact, the use of successive small quantities of acid produced appreciably different results from those given by the application of all the acid at one time. He wondered whether that feature had been taken account of in the process as here developed, and whether it would be a difficult

matter to incorporate in the system "series treatment" of the kind he mentioned.

Most members, he continued, would, however, be interested chiefly in the first portion of the paper. The centrifugal method of separating the wax described in the paper represented a reversal of the older procedure, and promised to be quite satisfactory. The paper read true, and should, he thought, be accepted at its face value, subject to the opportunity which everyone would seek of seeing the process in actual operation. A new process must be judged by two criteria: will it work and will it pay? The speaker said that he was not quite sure that the meeting had enough information on either of those points. As the Chairman has already indicated, the implication was that the new process of wax separation was only passing out of the development stage to the large scale. It was not a very large scale after all, and the speaker had gathered that most of the tests on the wax had been carried out on the smaller original test plant after shorter runs on the larger centrifuge which had been installed had proved satisfactory. He invited correction, but that was the way in which the paper had appeared to read.

When a new heavy solvent like trichlorethylene was prepared for use, technologists wanted to know the anticipated cost of the material on the scale on which it would have to be used, and how this would affect the losses which were bound to occur. It was all very well to say that the process would work on a vapour-tight enclosed system, but there was no such thing. No indication had been given of how often the solvent was used during the complete cycle. In refining a stated quantity of oil, what was the actual amount of trichlorethylene used? How many times was it brought into operation by being taken off and the distillate put back into the system again? What were the actual losses? What were power consumptions per unit throughput? What was the method and what the cost of continuous removal of the soft wax? That was the kind of information that was required in order to make a complete picture.

Dr. F. H. Garner raised the point as to which method was used for the estimation of pour point. In the paper pour points were quoted showing a difference of 2° F., which was not in accordance with the A.S.T.M. method. It was a matter of some considerable difficulty to determine pour points with an accuracy of 2° F.

In the acid refining process there were three outlets, one for the acid, one for the sludge and one for the refined oil. Normally, with lubricating oil distillate, one would not expect to have very much free acid if the process of mixing had been complete, and he therefore enquired under what conditions it was necessary to use the outlet for the free acid.

Mr. E. Thornton remarked that the impression given by the paper of the dewaxing of lighter oils was a very favourable one, but he regretted that that impression had come to wither a little as he had looked more closely at the tables. The only oil that was at all similar to the kind of cuts he was used to handling had, regrettably, the same sort of gap between the centrifuge temperature and the pour point that one obtained with the Sharples' process. This fact seemed important, because when all had been said about the amount of solvent needed, if the weight and the specific heat were taken together, there was not a great difference in the refrigerating requirements between the two kinds of solvent. The table showed that the lower specific heat with the higher gravity would just about cancel out, so that the question would turn into one of volume to be chilled.

It was more difficult and more costly to cool the lower one went, and if it were possible to obtain a process that would give a certain pour point with —22° F. it would be much cheaper than appeared from a mere comparison of temperature with a process that required —40° F. It was just that drop from —22° F. to —40° F. that was so expensive.

The speaker said that he would be interested to know whether any further comparisons had been made on very heavy oils like the last ones given in the table; whether the lecturer had any direct comparison between the dewaxing by the trichlorethylene method in the 40–60 proportions used and a similar dewaxing on a parallel oil by the benzine method using a ratio of 70–30. He asked whether there was any evidence that such a process decreased the gap between the centrifuging temperature and the pour point.

Other speakers had mentioned that any factor which gave a better cloud point for the same pour point was very important. Pour point had to be determined, and there might be some ambiguity about determining it, but cloud point, if it was not quite good enough, did not have to be determined; it was only necessary to see it in a bottle. There was no question that, whatever its real utility might be, the cloud point would be of very great importance as a "sales" point.

The Sharples' people themselves were more inclined to estimate dewaxing by cloud point than by pour point with very viscous oils. For that reason the speaker wanted information on the heavy oils rather than on the light ones, which were convincing in themselves.

It would, he continued, be possible to say a good deal on the acid side, but as he had had the pleasure of working with Dr. Backlund and of studying his results, his remarks might not

be germane to the meeting. It was not, however, to be taken as an unchallenged assumption that a long time in contact was necessarily an evil thing in acid treatment. In lubricating oil refining it was quite common to encounter twenty-four and thirty-six hour settlings, which, as far as had yet been found, could not be shown to give inferior oils to the same batch of acid-treated oil, whether centrifuged or otherwise. Moreover, these was a very well-known continuous acid treatment of kerosines in extensive use, and the time was long passed when the efficiency and economy of this method could be questioned.

On the vexed question of P.D., while new information was always welcome, his experience had been that continuous counter-current treatment, without reference to short time of contact, had achieved refining with cracked spirits with very low acid consumption and no difficulty about colour; whereas the speaker and his colleagues would be prepared to consider the new process, their own refining experience gave no evidence that a long time of contact was necessarily a bad thing.

Mr. J. E. Hackford enquired about the treatment of gasoline by this process. One of the speakers had discussed the necessity of adding one fraction of acid after the other, and said that an American firm had developed a method of treating cracked gasolines in which the acid was run through five centrifuges for a period of one-fifth of a second each in series. What was the drop in the octane number (C.F.R.) of the resultant gasoline by the present method? The revolutions of the American centrifuges were 17,000 per minute, and the speaker asked at what revolutions the present machine worked when it was being used for a similar purpose.

He also pointed out that difficulties had been experienced on account of the dilution of the acid and subsequent corrosion, especially when a machine was working at 17,000 r.p.m. for twenty-four hours a day, and there was likely to be a heavy maintenance cost.

He asked for evidence concerning the use of these centrifuges for soda treatment of gasolines, especially when a doctor solution was used.

Mr. H. Moore said that several people had put forward acid treatment followed by centrifugal separation. All claimed that a short contact time was a distinct advantage, but the speaker did not know that claim had ever been proved. Moreover, they all stated that oxidation should be avoided at all costs, and he was not convinced on that point. He had had experience of mechanical agitation in batch processes, and of air blowing in batch processes, and foremen who had operated these methods had in some cases assured him that the finished product of the air blown process was

appreciably better in colour than that obtained by mechanical agitation. He therefore considered that it was not to be accepted without supporting evidence that the use of air was a disadvantage.

Another question concerned the use of centrifugal pumps as mixers. The speaker said that some people who had been experimenting on those lines had informed him that centrifugal pumps were inefficient for mixing, as compared with special mixing machines. He asked the lecturer whether he had had any experience on this point.

It was said that by the batch process cracked gasoline was turned out with an octane number of 50, as against a number of 70 by the continuous process. The figure of 50 with cracked gasoline seemed extremely low, and the speaker wondered whether it had been obtained by washing the whole of the unsaturated components out of the spirit or by a normal acid treatment.

Mr. A. A. Ashworth wrote subsequently :—

With regard to the first part of the paper, the subject is most interesting for two separate reasons, which are, to a certain extent, distinct from each other.

The first reason is the use of a chlorinated hydrocarbon on a commercial scale as selective solvent in the separation of wax from lubricating oil distillates.

The second is the use of a centrifuge for the separation of the wax, taking advantage of the fact that the dissolved oil is heavier than the separated wax which is thus enabled to be continually withdrawn from the centrifuge. The process gives the refiner the ability to separate the whole of the wax in one operation, whereas, in all former commercial processes, two operations were necessary, one to separate the filterable or macrocrystalline wax and the other to separate the microcrystalline or amorphous wax. The separation of the wax in two processes involved the provision of two different plants and thus the new process presented by Dr. Backlund should effect a great saving in plant.

The use of a chlorinated hydrocarbon as selective solvent has been the subject of much experiment in the laboratory in the U.S.A., and several of these hydrocarbons have been tried. In a paper printed in the Journal of Industrial and Chemical Engineering, of date April, 1932, Messrs Carlisle and Levine advocated the use of dichloromethane. In some respects this would seem to have some advantages over the trichlorethylene used by Dr. Backlund. The main advantage in the writer's mind is that the separated wax was always crystalline and could be separated as an oil-free wax in a filter press, and thus avoid the redistillation which would seem to be necessary with wax separated by the use of trichlorethylene. The writer would like to ask Dr. Backlund whether the wax produced by his process is a filterable wax or whether it is

partly of the microcrystalline type. Has he ever experimented with dichloromethane?

The writer has not been able to gather from the paper whether it is more advantageous to separate the wax before or after the chemical treatment. From figures given it would seem that there is a better separation when operating on a residue than on a distillate in that a closer approximation is obtained between the cooling temperature and the pour point of the dewaxed oil. This would indicate that the process is better adapted for the separation of microcrystalline wax than of macrocrystalline. It is known that chemical treatment tends to the conversion of the former into the latter owing to the removal of substances which act as dispersoids of the wax crystals.

With regard to the second part of the paper dealing with the removal of acid sludge from acid-treated oil, the writer would like to ask what proportion of the acid used for treatment is recovered from the centrifuge and what is the condition of this recovered acid. Is it sufficiently clean to be used for the treatment of a further batch or is it diluted by the water formed by the chemical action of the acid on the oil?

What is the evidence that some oils require a rather considerable period in the reaction vessel? Such requirement would rather point to an insufficient agitation of a viscous oil with the acid. The completion of the mixing in a separate vessel under static conditions would be a poor substitute for better mechanical mixing, and the writer would not consider an oversize centrifugal pump as the most efficient mechanical mixer.

Dr. N. O. Backlund, in reply, wrote:—

It is true that this power consumption per unit of dewaxed oil is greater with this method than with the benzine method. With the latter method the separator requires about 1·5 h.p. at about 250 litres/hour capacity, whereas this separator consumes about 5·5 h.p. at a capacity of 400 litres of oil per hour.

As will be shown in the following, however, this difference plays a very small part in the comparative economy of the two methods.

The fact that with this method the cloud point of the oil is very close to the pour point (contary to the case with the benzine method) is due to the different solubility of certain waxes at low temperature and under pressure in the different solvents used in the two methods.

It may be presumed with a fair degree of certainty that the "clouding" of the oil is caused by a small quantity of quite soft wax remaining in the oil after dewaxing, and having no material influence on the pour point, whereas it causes the above-mentioned undesired clouding of the oil before the latter solidifies.

These waxes crystallise later in benzine than in tri, on cooling

down to low temperatures. Moreover, comparative tests have shown that a larger amount thereof remains in the benzine-dewaxed oil than in the tri-dewaxed oil, after the solvent has been distilled off. Thus these waxes cause a higher cloud point of the benzine-dewaxed oil.

The fundamentally different modes of operation of the two methods means that part of the wax separated by the benzine method and thrown out against the periphery of the separator bowl goes into solution, due to the high centrifugal pressure prevailing there. With the tri method, on the other hand, the separated wax moves inwards, towards the centre of the bowl, and is thus not exposed to any high centrifugal pressure. Consequently, much less wax is redissolved.

The lower sensibility of this method to the presence of crystalline wax is due to the greater difference in specific gravity between the two components to be separated. Moreover, it has been observed that crystalline wax, when dissolved in tri, has much less tendency to crystallize as a network than it has when dissolved in benzine.

The relation between the pour point of the dewaxed oil and the degree of cooling depends on the nature of the wax present in the oil, and especially on the relative quantities of soft and hard wax.

The larger the quantity of soft wax, the greater is the difference between the lowest cooling temperature and the pour point obtained.

Regarding the possibility of filtering the separated wax, it may be said that, as long as the latter is of macrocrystalline structure, it can, of course, easily be filtered.

The question was asked several times whether the dewaxing should be carried out before or after the acid treatment of the oil. In regard to the tri-method, this depends entirely on economical considerations.

An acid treatment prior to the dewaxing is not necessary, since tri dissolves asphaltic matters (inhibitors) which impair the crystallization of the wax. In benzine solutions, on the other hand, these asphalts partly remain in a colloidal state, thus preventing satisfactory crystallisation of the wax and partly precipitated, thus impairing the continuous separation.

The tri can be used over and over again for a practically unlimited time.

In cases when the oil to be dewaxed contains light fractions, a subsequent fractioning of the tri may be necessary.

Any detrimental dissipation of chlorine and consequent formation of hydrochloric acid does not take place, provided that a certain temperature is not exceeded, as mentioned in the paper.

An absolute safeguard in this respect can be obtained by re-distilling over caustic soda.

When considering the necessary quantities of both kinds of solvents—their specific gravity, specific heat, etc.—one easily gets the impression that the chilling requires approximately the same number of calories.

The fact that this process nevertheless requires a much smaller chilling plant is due to the considerably shorter time of chilling, viz., only 12–15 hours, against 60–72 with the benzine method.

For 1000 kilos of oil at the dewaxing proportions of 55 oil : 45 tri and 35 oil : 65 benzine, respectively, the calories required (for a plant for dewaxing 40,000 kgs. oil per day) are approximately as follows :—

	Tri.	Benzine.
Kg. calories per hour for chilling	105,000	324,000
Kg. calories per hour for distilling off the solvent	94,800	145,500

The approximate costs of dewaxing at the above-mentioned daily output are shown below, in U.S. dollars per 1000 kgs. of oil :—

	Tri.	Benzine.
Chilling	0·232	0·702
Distillation	0·052	0·079
Losses of solvent	0·540	0·270
Power consumption of separators	0·043	0·023
Depreciation and interest	1.359	1·890
	2·226	2·964

For other dilution proportions the corresponding total cost of dewaxing is approximately :—

Oil : Tri.	$ per 1000 kgs.	Oil : Benzine.	$ per 1000 kgs.
40 : 60	3·096	20 : 80	4·680
50 : 50	2·646	25 : 75	3·924
60 : 40	1·764	30 : 70	3·330

With regard to acid refining, neither as far as the separators nor the axuiliaries are concerned has any excessive mechanical or chemical wear been observed, when the proper material of construction is used and the machines are properly operated. This statement is based on seven years' operating experience.

The amount of free acid contained in the mixture of oil and tar to be separated varies within wide limits, depending on the separating temperature. The acid is highly diluted and contains tar in solution and can thus not be reused without previous regeneration.

Experience has shown that different oils require entirely individual treatment in regard to percentage of acid, temperature and time of reaction. These factors depend on the origin and production of the oil and have to be determined in each particular case.

By correctly determining these factors a complete "ripening" of the acid tar is guaranteed, and thus also the complete separation from the oil.

Integration and Pulsation Errors in Measurement of Quantities of Gas Flowing Through an Orifice.*

By D. Gilmour.

Preface.—By G. P. Melville.

Attention was primarily attracted to the integration of irregular flow rates by the fluctuating nature of gas flows from many of the producing wells in the Singu Field during a period, when casing-head pressures were influenced by a fluctuating gas collection line pressure, which was dependent upon the balance between supply and fuel demand. Gas flows throughout the entire system were therefore variable. It was very evident that the simple integration of orifice meter charts and the existing methods of application of $Q = C\sqrt{\frac{H.P.}{G.T.}}$ cu. ft. did not satisfy the nature of these flows and that considerable errors were incurred. The aggregation of all chart errors assumed large proportions and, despite careful field supervision of the gas system, it was impossible to arrive at any satisfactory balance between "gas supplied" and "gas distributed" to field consumers.

The installation of boosters for gas collection purposes and maintenance of steady gathering line pressures reduced fluctuating and pulsating effects from many producing wells, and it was therefore possible to classify wells according to the nature of flows produced, such as constant, regular, fairly regular, etc. The application of formulæ for elimination of integration and pulsation errors was therefore restricted to wells of the irregular classes.

The introduction of straight and intermittent methods of gas lift production presented similar problems of erratic and rapidly pulsating flows, and accuracy of orifice chart calculation became one of extreme importance in order to establish gas lift efficiencies and compressor economies.

In oilfields, such as Singu, where there are producing wells of the irregular gas flow type, and gas/oil ratios form an extremely important feature of production control, errors arising from chart integration, unless eliminated, are likely to indicate larger volumes of gas flowing than is actually the case, and therefore higher casing-head pressures than necessary are imposed, involving unnecessary production restriction.

The author in his paper shows the nature and extent of errors

* Paper received October 26th, 1932.

incurred "in integration by popular methods." He also explains by simple mathematical devices the nature of the meter errors involved in measurement of pulsating flows and evolves formulæ for the calculation of the reduction of these errors, which, if neglected, adversely affect field operations.

The practical significance of the note will be obvious to all interested in orifice measurement and oilfield technique.

Introduction.

The initial purpose of this paper was to offer a report upon an investigation, conducted in the Singu Field of the Burmah Oil Company, into existing pulsation errors in meters and also to explain the means adopted for the reduction of these errors to an inappreciable amount in an economic manner.

As, however, the argument is a particularisation of the general argument concerning the errors arising in the integration of irregular and vibratory flow, a summarisation of the general discussion may be of considerable value to those who are not intimately familiar with the subject.

A perusal of a representative portion of the literature on orifice measurement has failed to reveal any serious attempt to indicate in detail the errors incurred in integration, by popular methods, of erratic flow or by the use of small time-scale on charts. In practice, there is an obvious tendency to sacrifice accuracy to simplicity in measurement and computation, and, while this is often justifiable from an economic standpoint, the computant should be fully conversant with the nature of the errors thus incurred. This important subject is only faintly stressed in current books of directions, published by the meter manufacturers—so faintly that the operator may be excused in assuming that the errors, caused by the methods suggested in these books of instructions, are relatively small. The purpose of this discussion is to show the nature of these errors by simple methods of demonstration.

Explanatory Preface.

The formula for the calculation of the rate of flow through an orifice at any instant is, of course, a differential equation with respect to time. Consequently accurate simplification in integration can only be achieved for any specified period, during which the variables in the differential equation are constants or functions of the time, or by the use of some form of planimeter, capable of determining the *mean square root* of each variable.

The formula, used commercially for the determination of the rate of flow through an orifice, is generally quoted as :—

$$Q = C\sqrt{\frac{H.P.}{G.T.}} \text{ cu. ft. at N.T.P.} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

in which Q=the quantity of gas passing in cu. ft. at N.T.P. per hour;

C=a coefficient depending upon :—

(*a*) the sizes of orifice and pipe;

(*b*) the duration of the flow;

(*c*) the basis of measurement of the unit;

(*d*) the ratio of the differential to the pressure; and

(*e*) the position of the pressure tappings on the line.

(In common practice "C" in U.S.A. is made to represent the rate of flow through the orifice per hour, when "H" and "P" are unity, "G" is some fixed value and "T" is base temperature.)

H=the differential across the pressure tappings, in inches of water.

P=the static pressure in the line at one of the tappings, in pounds/sq. in. absolute.

T=the flowing temperature of the gas, in degrees Fahrenheit absolute.

G=the specific gravity of the gas with respect to air.

Equation (1) being, however, the equation of the *rate* of flow at any instant, the values of "H," "P," "G" and "T" to be inserted in the equation should be the simultaneous values at the particular instant and equation (1) written thus :—

$$\frac{dQ}{dt} = K\sqrt{\frac{H.P.}{G.T.}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2$$

Integrating equation (2) generally, we get :—

$$Q = Kt\int_0^t \sqrt{\frac{H.P.}{G.T.}}\, dt \text{ cu. ft.} \quad \ldots\ldots\ldots\ldots\ldots \quad (3)$$

Since H, P, G and T are variables independent of the time, direct integration is only possible for any period, t, during which H, P, G and T are *constant*, when equation (3) becomes :—

$$Q_{t-t} = Kt\sqrt{\frac{H.P.}{G.T.}}\Big]_0^t = Kt\sqrt{\frac{H.P.}{G.T.}} \text{ cu. ft.} \quad \ldots\ldots\ldots\ldots \quad (4)$$

Equations (4) and (1) are identical, but the derivation of (4) makes clear that direct integration is only possible for a period, during which H, P, G and T are constant.

Let us assume that, during the period of measurement, G and T are constant. Equation (3) may then be written:—

$$Q = Kt \int_0^t \sqrt{\text{H.P.}}\, dt \text{ cu. ft.} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

If, in successive equal increments of time, the differential, H, has the constant values H_1, H_2, H_3 . . . . H_n and the static pressure has the corresponding constant values P_1, P_2, P_3 . . . . P_n, then, since integration can only be carried out directly for periods during which H and P are both constant, it is necessary to summate the particular integrals for each time increment, δt.

Thus $Q_{t-n} = K(\sqrt{H_1P_1} + \sqrt{H_2P_2} + \sqrt{H_3P_3} + \ldots + \sqrt{H_nP_n})$ cu ft. (6)

If, however, in order to simplify integration, the square roots of arithmetic averages of pressure and differential are substituted, then the approximate value of:—

$$Q_{t-n} = K_n \sqrt{\frac{(H_1+H_2+H_3+\ldots+H_n)(P_1+P_2+P_3\ldots+P_n)}{n \times n}} \text{ cu. ft.} \quad (7)$$

Equation (7) only approximates to the value of the true integration (6) when:—

$$\sqrt{(H_1+H_2+H_3+H_4\ldots+H_n)(P_1+P_2+P_3+P_4+\ldots+P_n)}$$

is nearly equal to:—

$$\sqrt{H_1P_1} + \sqrt{H_2P_2} + \sqrt{H_3P_3} + \sqrt{H_4P_4} + \ldots + \sqrt{H_nP_n} \ldots. \quad (8)$$

(The approximation (8) depends upon G and T being constant throughout.)

Assumptions.

It is presumed throughout this discussion that the orifice head varies with Q^2, and that the type of meter employed is fitted with a fluid U-tube. It is also presumed that the flow charts require to be integrated without the aid of square root planimeters by the quickest and most economic means at the computants' disposal.

It is assumed that complete, continuous records of all factors in the flow equation, with the exception of the specific gravity, are maintained throughout the period of measurement, and that the specific gravity determinations are made at sufficiently short intervals to ensure that the degree of variation of this factor throughout the period of measurement is known.

Classification of Flows in Practice.

In actual practice, flows of gas may be grouped into the following general classes for the purpose of integration:—

1. Regular flow throughout the whole period of measurement,

during which the measurement factors vary less than 20 per cent. of the *maxima*. (See Appendices 1, 3 and 4.)

2. (*a*) Flow, during which one factor only varies very appreciably, the rate of variation being sufficiently slow to ensure that no appreciable error is incurred by integration for each hourly period (*i.e.*, the total variation is less than 20 per cent. of the maximum value during any one hour). (Appendix 1.)

2. (*b*) Flow, during which two factors vary appreciably during the period of measurement, the rates of variations in both cases being sufficiently slow to ensure that no appreciable error is incurred by integration for each *hourly* period. (Total variation in both cases is less than 20 per cent. of the maximum value during any *one* hour.) (See Appendices 3 and 4.)

3. (*a*) Flow, during which one factor only varies very appreciably, the rate of variation being too great to ensure accurate measurement by integration for each hourly period. (See Appendix 1.) The duration of each successive period, during which the variable does not change more than 20 per cent. of the maximum value, can be determined from the flow chart. Integration for short periods of 15 minutes or less must be resorted to.

3. (*b*) As in 3 (*a*), but for two variables. (See Appendix 4.) In this case greater care in the determination of the "time difference" between simultaneously recorded values of the two variables must be taken than for the previous examples.

4. (*a*) "Vibrating" flow, during which one variable only changes appreciably, the successive periods of regular or uniform values being of so short duration that they cannot be determined from the flow chart. The rate of change is, however, *sufficiently slow* to permit the recording mechanism to record faithfully the true values of the variable. In this case the time scale is too small and the resultant graph appears as a broad serrated band of ink round the chart. A chart, recorded with a fast clock, is necessary for the determination of the true shape of the graph. (See Appendix 2.)

4. (*b*) As in 4 (*a*), but for two variables. (See Appendices 5 and 6.)

5. Rapidly vibrating or pulsating flow, during which the rate of change *is too fast* to permit the recording mechanism to record the true value of the variables, *due to the high inertia of the recorder*. In this case the means of successive maximum and minimum values are recorded by the meter itself. The errors given in Appendices 2, 5 and 6 are consequently directly applicable to the meter itself, regardless of any further errors incurred in integration of the chart. No form of meter has been devised for measurement

of pulsating flow. If the operator wishes to measure this flow, he must eliminate the pulsation by the best means at his disposal. Beans and throttling devices in the meter itself are entirely *useless*, despite the fact that they are supplied, fitted or recommended by many orifice meter manufacturers. Any attempts to rate the meter, when measuring pulsating flow, by means of the equation in Appendices 2, 5 and 6 should likewise be avoided, unless the pulsations have been reduced so that their effects are practically negligible.

Summary of Methods of Integration.

Charts of flows, which fall into the general classes 1–3 (*b*) can be integrated with a high degree of accuracy by any computant, and the errors, incurred by substituting the square root of means, as indicated in Appendices 1, 3 and 4, can be eliminated, if the integrations are made for periods, during which the variables do not change in value beyond the safe limits indicated therein. If "direct reading" charts are employed, the safe limits are determined by using ordinary linear scale (1st power) to determine "r" and "s," or by taking the square root of the ratios obtained on the scale of the direct reading charts. In cases, where the variation is cyclic, the application of a correction factor for the "planimetered" flow is justified on economic grounds, in order to simplify computation. The use of the ordinary radial planimeter should be entirely restricted to calculation of flows, during which the variables do not exceed the limits indicated in Appendices 1, 3 and 4, otherwise the errors incurred will be of the nature determined therein.

Charts of flows, which fall under the categories 4 (*a*) and 4 (*b*), *cannot be accurately integrated without supplementary information* being supplied by a fast clock meter, employing a much greater time scale. Usually, in vibrating flow, the curves of the variables, pressure and differential, are reproduced with cyclic regularity, but the values of the variables at any instant during each cycle may differ from the similar values for the preceding cycle. If, however, the true shapes of the time curves are similar, the square root means for each cycle can be expressed with reasonable accuracy in terms of the square roots of maximum or arithmetic mean values for that cycle. A reasonably accurate method can thus be devised for the integration of small time-scale charts, on which records of the types of flow above mentioned are described. If, however, it is economically possible, a record on a larger time-scale chart should be maintained, particularly in cases where the variations are not cyclic.

Accurate measurements of flows in the catagories 4 (*a*) and 4 (*b*)

could be easily obtained if manufacturers supplied fast clockwork mechanisms and a cylindrical type of chart in preference to the circular or disc chart.

The use of pulsation bushings, and other meter-damping devices, merely deludes the operator into assuming a false standard of accuracy, by increasing the potentiality of the meter to error. The damping of an orifice meter increases the inertia of the recording mechanism, which *already* lacks sensitiveness, due to inherent inertia, thereby transferring types of flows, which would normally fall under categories, 4 (*a*) and 4 (*b*), into the class described under 5.

There being no fixed line of demarcation between the classifications adopted in this note, each operator must differentiate between and classify his charts relative to :—

(*a*) the time scale employed by the meter in question, and

(*b*) the degree of inertia of the meter.

Elimination of Pulsation Errors (Class No. 5).

The elimination of vibration and pulsation can only be achieved by inserting between the orifice and the source of flow a reservoir of sufficient capacity to ensure that, for a negligible change in the differential across the measuring orifice (*i.e.*, for a negligible change in reservoir pressure), the change in the contents of the reservoir is greater than the difference between the rates of flow into and from the reservoir.

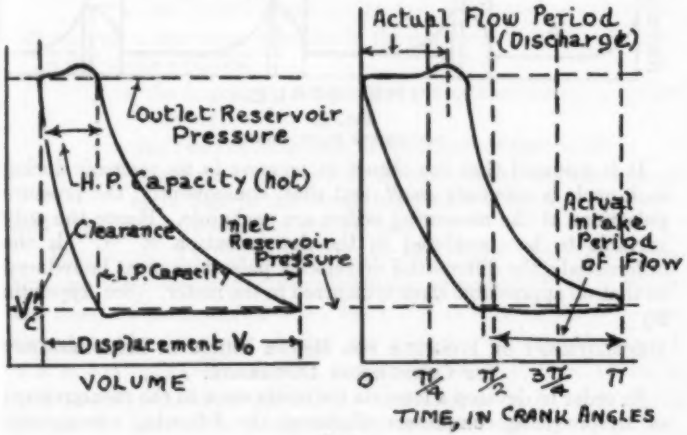


Fig. 1.

The elimination can be achieved in one or more stages of throttling, but, for the purpose of this note, it is assumed that no other appreciable throttling exists between the source of pulsation and the measuring orifice (*i.e.*, all throttling is effected by the measuring orifice itself).

As reciprocating gas compressors are the commonest source of pulsation in practice, the following discussion refers principally to rapidly pulsating flows of the type produced by modern compressors. The equation for determination and elimination of meter error could be applied, however, to other types of pulsating flow.

Reduction of Pulsation Errors: Discharge Pulsations, Measurement of Compressor Discharge.

If we assume that the input and output rates of flow for the discharge reservoir are fairly accurately represented by Fig. 2. it is possible to express the capacity, C, of the discharge reservoir, which is required for the elimination of pulsation, in known factors :—

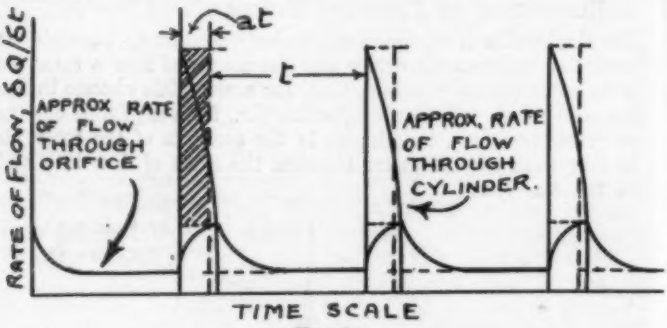


Fig. 2.
DISCHARGE FLOW CHART.

It is assumed that the *change in pressure in the reservoir* during each cycle is *extremely small*, and that, consequently, the pressure pulsations at the measuring orifice are negligible. Hence the only variable to be considered in the determination of "C" is the differential; the differential or velocity pulsations must be reduced so that no appreciable error is incurred in the meter. (See Appendix 2.)

Development of Formula for Meter Error in Measurement of Compressor Discharge.

In order to develop a formula for meter error in the measurement of reciprocating compressor discharge the following assumptions are also made :—

(*a*) that the meter records the arithmetic mean of the maximum and minimum differentials during the cycle ;

(*b*) that, as the rate of piston displacement is known—(harmonic curve)—during the period of flow, if the curve of piston displacement with respect to time be modified in accordance with the pressure curve, recorded by the indicator, an approximate flow chart can be drawn ;

(*c*) that this flow chart can be replaced, for the purpose of simplification, by a " square form " flow, the period of flow from the compressor during each cycle being replaced by the period of equivalent, uniform, maximum rate of flow ;

(*d*) that, as the resistance to flow through the orifice is comparatively negligible, the period of equivalent, uniform maximum rate of flow through the orifice is of the same duration as for the flow from the compressor ; and

(*e*) that, the periods of equivalent, uniform, maximum rate of flow for the flows from the compressor and through the orifice, being of equal duration, commence and terminate simultaneously.

Assuming that the measurement is made with " full flow " connections :—

If D = the total discharge from the compressor per cycle, in cubic feet at N.T.P.

Then $D = Kt\sqrt{X}(a+r)$ cubic feet at N.T.P. (App. 2.)..(9)
$= A\sqrt{Pm}\,t\sqrt{X}(a+r)$ cubic feet, K being equal to $A\sqrt{Pm}$.

Where Pm = the mean pressure in the reservoir in lbs./sq. in. abs.

In the above equation—

X = the maximum differential across the orifice in inches of water

r = the ratio of minimum to maximum differentials.

a = the ratio of the period of equivalent, uniform, maximum flow to the remaining period of cycle,

and t (a+1) = duration of one cycle.

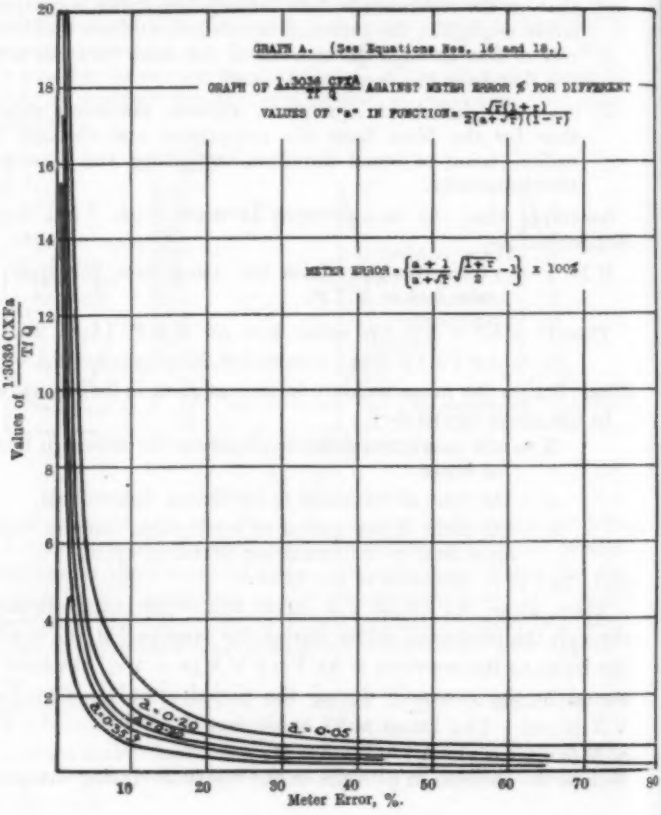
Then, since $A\sqrt{Pm}$ at $\sqrt{X}$ cubic feet = the total discharge through the measuring orifice during the same period, at, in which the input to the reservoir is $A\sqrt{Pm}\,t\sqrt{X}(a+\sqrt{r})$, the total gas stored in the reservoir during the period, "at," $= A\sqrt{Pm}\,t\sqrt{X}(a+r) - (A\sqrt{Pm}$ at $\sqrt{X})$ cubic feet at N.T.P. $= A\sqrt{Pm}\,t\sqrt{X}(a+\sqrt{r}-a) = A\,t\sqrt{Pm\,X}\,x\sqrt{r}$ cubic feet .....(10)

But as the increase in pressure in the reservoir during the period,

"at," is $\frac{X-rX}{27{\cdot}7}$ lbs./sq. in. $= \frac{X(1-r)}{27{\cdot}7}$ lbs./sq. in., for "full flow" connections, the total gas stored in the reservoir, because of the pressure increase, is $\frac{C\,X\,(1-r)}{14{\cdot}4\times27{\cdot}7}$ cubic feet, measured at the flowing temperature, Tf, in the reservoir and 14·4 lbs./sq. in.

∴ The gas stored, due to the pressured increase, $\frac{X(1-r)}{27{\cdot}7}$ lbs./sq in.

$= \frac{C\,X\,(1-r)}{14{\cdot}4\times27{\cdot}7} \times \frac{520}{Tf} = 1{\cdot}3036\,\frac{C\,X\,(1-r)}{Tf}$ cubic feet measured at 14·4 lbs./sq. in. and 60° F., where Tf = reservoir temperature (11)

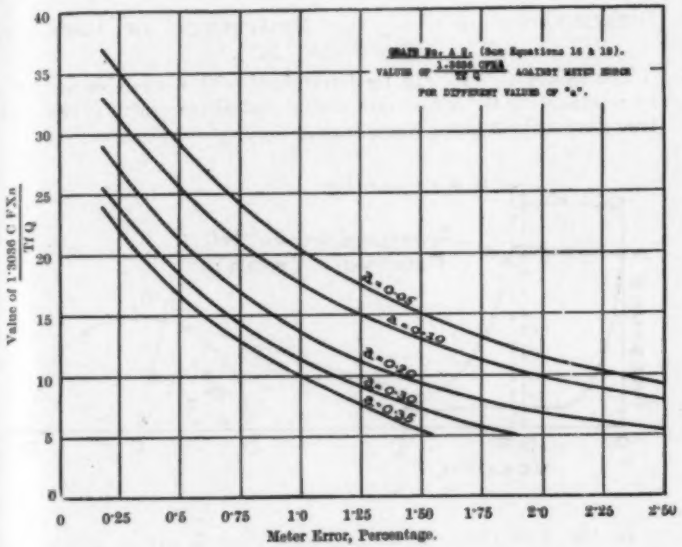

GRAPH A. (See Equations Nos. 16 and 18.)
GRAPH OF $\frac{1{\cdot}3036\ CfXa}{Tf\ Q}$ AGAINST METER ERROR % FOR DIFFERENT VALUES OF "a" IN FUNCTION $\frac{\sqrt{r}(1+r)}{2(a+\sqrt{r})(1-r)}$
METER ERROR $= \left\{\frac{a+1}{a+\sqrt{r}}\sqrt{\frac{1+r}{2}}-1\right\} \times 100\%$
Values of $\frac{1{\cdot}3036\,CXPa}{Tf\,Q}$
a = 0·20
a = 0·35
a = 0·05
Meter Error, %.

Equating the two values of the gas stored, as given by equations Nos. 10 and 11, we get:—

$$1{\cdot}3036\,\frac{C\,X\,(1-r)}{Tf} = A\sqrt{Pm\,X}\,t\sqrt{r} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (12)$$

But $\dfrac{A\sqrt{Pm\,X}\,t\,(a+\sqrt{r})}{t\,(a+1)} = Q$, where Q = the mean rate of flow in cubic feet at N.T.P. per second, t being also in seconds.

$$\therefore\ A\sqrt{Pm\,X}\,t = \frac{Q\,t\,(a+1)}{a+\sqrt{r}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (13)$$



$$\therefore\ 1{\cdot}3036\,\frac{CX}{Tf} = \frac{Qt\,(a+1)\,x\sqrt{r}}{(a+\sqrt{r})\,(1-r)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (14)$$

and $t\,(a+1) = \dfrac{1}{F}$, where F = frequency of pulsation in cycles per second.

Substituting, $1{\cdot}3036\,\dfrac{CXF}{Tf\,Q} = \dfrac{\sqrt{r}}{(a+\sqrt{r})\,(1-r)}$ ..... (15

Also, from Appendix 2, the meter error is :—

$$\left\{\frac{(a+1)}{(a+\sqrt{r})} \times \sqrt{\frac{1+r}{2}} - 1\right\} \times 100 \text{ per cent.} \quad \ldots\ldots\ldots\ldots (16)$$

and the average differential reading, Xa, of the meter is given by

$$X\frac{(1+r)}{2} \text{ inches, for "full flow" measurement} \quad \ldots\ldots\ldots (17)$$

∴ Equation No. 15 may be *written* thus :—

$$\frac{1{\cdot}3036\ CF\ Xa}{Tf\ Q} = \frac{\sqrt{r}\,(1+r)}{2\,(a+\sqrt{r})\,(1-r)}$$ where Xa = meter or U tube reading for "full flow" measurement ..... (18)

DETERMINATION OF "a" FOR MEASUREMENT OF DISCHARGE. (See Graph "E.").

The values of "a" can be determined with reasonable accuracy by representing the actual flow period and displacement period on a true time scale or crank angle scale.

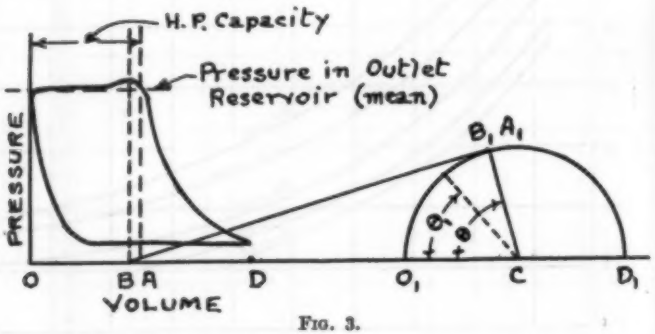


FIG. 3.

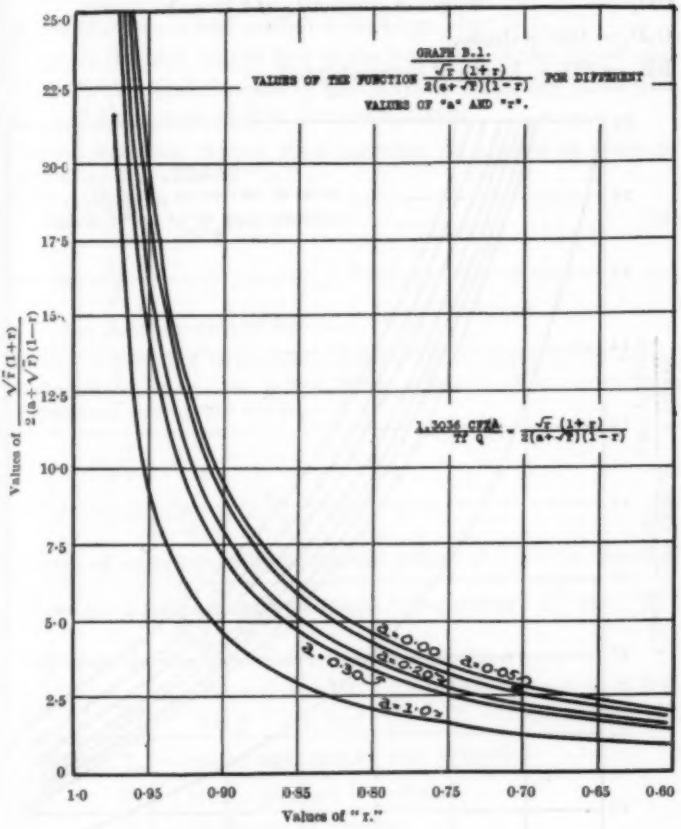
In the first place, if an indicator card is not available, the theoretical H.P. and L.P. capacities can be determined from the following formulæ :—

If Rc = the ratio, $\frac{\text{Clearance Volume, Vc}}{\text{Displacement Volume, Vd,}}$

then the L.P. capacity $= \left\{1+Rc-Rc\left(\frac{P_2}{P_1}\right)^{1\cdot1\cdot26}\right\} \times Vd.$

and H.P. capacity $= \frac{\text{L.P. Capacity}}{\left(\frac{P_2}{P_1}\right)^{1\cdot1/\cdot26}}$

$$\therefore \text{The theoretical H.P. capacity} = \frac{\left\{1+Rc-Rc\left(\frac{P_2}{P_1}\right)^{1/1\cdot26}\right\}Vd}{\left(\frac{P_2}{P_1}\right)^{1/1\cdot26}} \quad (19)$$



When P_2 = discharge pressure in lbs./sq. in. absolute,
and P_1 = intake " " " "

Having determined the H.P. capacity, Fig. 3. can be then drawn :—

OD represents the displacement volume to some suitable scale.

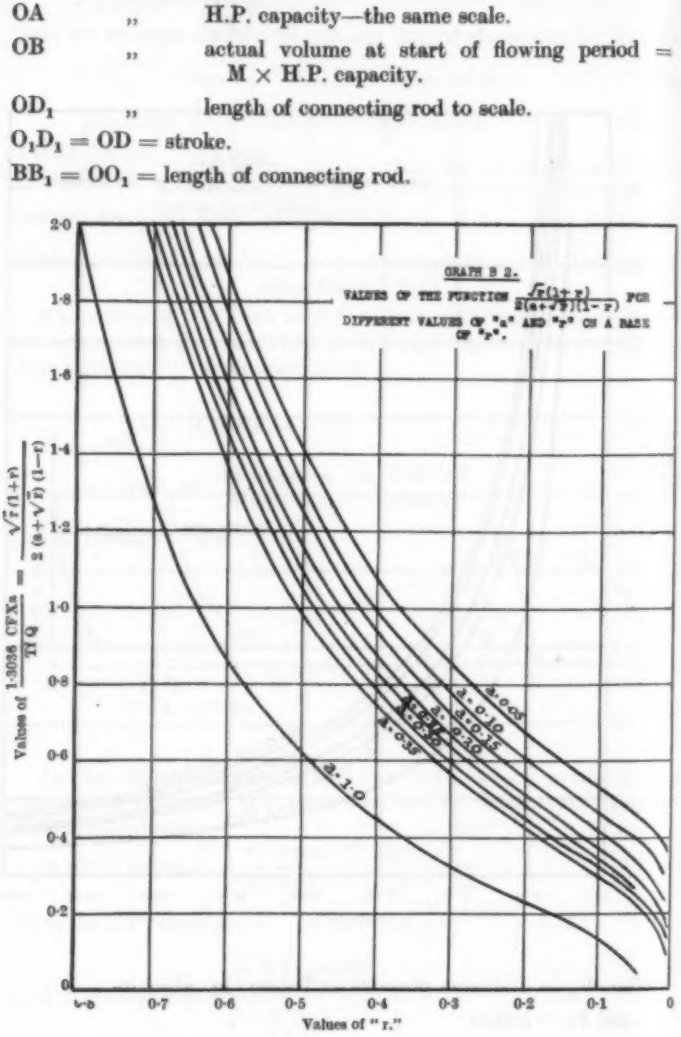
OA ,, H.P. capacity—the same scale.

OB ,, actual volume at start of flowing period = M × H.P. capacity.

OD_1 ,, length of connecting rod to scale.

$O_1D_1 = OD$ = stroke.

$BB_1 = OO_1$ = length of connecting rod.



The actual period of discharge flow is less than the period represented by the H.P. capacity, because the discharge valves do not open until the cylinder pressure is appreciably greater than the reservoir pressure, the actual compression curve lies below the theoretical, water cooling causes departure from the adiabatic, and piston slippage effects a further slight reduction.

The equivalent period of uniform maximum rate of discharge is less than the actual period of discharge, due :—

(*a*) To the high rate of flow at the beginning of the period, and

(*b*) To the rapid decrease in piston speed during the latter part of the period of flow (harmonic curve).

Two correction factors must therefore be applied in order to determine the value of " a " :—

$$M = \frac{OB}{OA} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (20)$$

$$N = \frac{\theta 1}{\theta} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (21)$$

θ = Actual period of flow.

Then θ_1 = period of equivalent uniform rate of maximum discharge, differential during this period being equal to X in. (maximum differential during the cycle).

$$\therefore \frac{a}{a+1} = \frac{\theta_1}{\pi}$$

$$\therefore a = \frac{\theta_1}{\pi - \theta_1} = \frac{N\theta}{\pi - N\theta} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (22)$$

Curves of experimentally determined values of " a " for values of $\frac{P_2}{P_1}$ are given for intake and discharge. (See graphs " E " and " H.")

Q may also be determined from the equation :—

$$Q = \left\{1 + Rc - Rc\left(\frac{P_2}{P_1}\right)^{1/1\cdot 26}\right\} \frac{Vd}{14\cdot 4} \times P_1 \times \frac{520}{T_1} \times F \text{ cu. ft. at N.T.P. per second.} \quad (23)$$

Where T_1 = intake temperature near cylinder ;

P_1 = intake pressure to cylinder ;

Vd = displacement volume ;

Rc = clearance ratio = $\frac{\text{Clearance}}{\text{Displacement}}$, and

F = number of strokes/second.

Table of Percentage Meter Errors for Different Values of "a" and "r," "a" being Less than Unity.

(See also Table No. II., Appendix No. 2.)

For Measurement of Discharge from Compressor.

Values of "a."	Values of "r."							
—	0·95	0·90	0·85	0·80	0·60	0·40	0·20	0·10
0·05	1·2	2·5	3·9	5·4	13·9	28·7	63·5	112·6
0·10	1·0	2·3	3·5	4·9	12·5	25·7	55·7	96·0
0·15	0·9	2·1	3·1	4·4	11·3	23·0	49·6	—
0·20	0·8	1·8	2·8	4·0	10·1	20·6	43·6	72·4
0·25	0·8	1·6	2·6	3·6	9·1	18·4	39·1	—
0·3	0·7	1·5	2·3	3·2	8·1	16·4	34·8	56·4
0·35	0·7	1·3	2·1	2·9	7·3	14·8	31·2	—
0·4	0·6	1·2	1·8	2·6	6·5	13·4	27·9	45·0
0·45	0·5	1·1	1·6	2·3	5·8	12·1	25·1	—
0·5	—	—	1·4	2·0	5·2	10·9	22·7	36·3
0·55	—	—	1·2	1·8	4·7	9·6	20·3	32·7
0·6	—	—	—	1·7	4·1	8·6	18·3	29·5
0·7	—	—	—	—	3·0	6·8	14·8	24·1

Table of Values of the Function $\frac{\sqrt{r}\,(1+r)}{2(a+\sqrt{r})(1-r)}$ *for Different Values of "a" and "r."*

(See equation No. 18.) "a" less than unity.

Values of "a."	Values of "r."									
—	0·95	0·90	0·85	0·80	0·60	0·4	0·2	0·1	0·05	0·02·
0·05	18·55	9·024	5·849	4·262	1·878	1·081	0·6745	0·5277	—	—
0·10	17·68	8·594	5·563	4·047	1·771	1·007	0·6130	0·4643	—	—
0·15	16·90	8·204	5·304	3·854	1·675	0·9428	0·5616	0·4145	—	—
0·20	16·17	7·847	5·060	3·667	1·590	0·8861	0·5112	0·3744	0·289	0·2115
0·25	15·52	7·518	4·852	3·517	1·511	0·8360	0·4811	0·3414	—	—
0·30	14·89	7·218	4·652	3·370	1·441	0·7912	0·4488	0·3137	0·236	—
0·35	13·34	6·939	4·470	3·233	1·337	0·7508	0·4027	0·2900	0·2153	0·1497
0·50	12·89	6·220	3·998	2·887	1·215	0·6513	0·3542	0·2111	—	—
0·60	12·07	5·82	3·736	2·694	1·127	0·5099	0·3204	0·1880	—	—
0·70	—	—	—	—	—	—	—	—	—	—

EXCERPTS FROM TESTS.

Results of Test No. 1.—Measurement with "Full Flow" Connections of Compressor Discharge.
"C," "F," "Tf" Constant. "Q" Nearly Constant. XA Variable. Orifice Diameter Variable.

"C" Capacity of outlet reservoir in cu. ft.	"F" Frequency of pulsation in cycles per sec.	"Q" Mean rate of flow in cu. ft. at N.T.P. per sec.	Flowing temp. in reservoir (mean) in degrees Fahrenheit.	Diameters. (Standard) internal pipe diameter in inches.	Diameters. Orifice diameter in inches.	"Full flow" differential recorded by U-tube or meter; XA in inches of water.	Pressures. Intake in inches mercury vacuum.	Pressures. Discharge in pounds per square inch.	Value of factor "a."	Value of $\frac{1{\cdot}5036\ CFXA}{TfQ} = \frac{\sqrt{r}\,(1+r)}{2\,(a+\sqrt{r})\,(1-r)}$	Value of factor "r."	Value of calculated meter error, percentage $-\left\{\frac{a+1}{a+\sqrt{r}}\sqrt{\frac{1+r}{2}}-1\right\}\times 100$	Actual meter error %.
30·87	5·00	8·205	164	8	4	5·4	1·5	13·9	·30	·2130	·034	94·0%	74·5%
30·87	5·01	9·071	164	8	3·5	9·8	0	12·0	·305	·3505	·125	47·3%	49·5%
30·87	5·01	8·81	164	8	3·0	13·8	1·0	19·0	·25	·506	·218	36·3%	42·0%
30·87	5·01	7·98	164	8	2·5	19·5	2·5	19·0	·25	·7890	·380	19·6%	25·4%
30·87	5·01	7·95	164	8	2·25	26·0	2·5	18·0	·25	1·058	·484	14·8%	16·1%

EXCERPT FROM TEST.

Results of Test No. 2.—Measurement with "Full Flow Connections," of Compressor Discharge.
Orifice Diameter, "C," "F," "Tf" Constant. "Q" and XA Variable.

"C" Capacity of outlet reservoir in cu. ft.	"F" Frequency of pulsations in cycles per sec.	"Q" Mean rate of flow in cu. ft. at N.T.F. per sec.	Tf Mean flowing temp. in reservoir in degrees Fahrenheit.	Diameters. Internal of pipe (standard) in inches.	Diameters. Orifice in inches.	XA differential recorded by U-tube or meter in inches of water.	Pressures. Intake in inches mercury vacuum.	Pressures. Discharge in pounds per square inch.	Value of factor "a."	Value of function, $\frac{\sqrt{r}\,(1+r)}{2\,(a+\sqrt{r})\,(1-r)}$	Value of factor "r."	Calculated meter error per cent. $\left\{\frac{(a+1)}{(a+\sqrt{r})}\sqrt{\frac{1+r}{2}}-1\right\}\times 100$	Actual meter error per cent.
30·87	5·01	6·509	178	8	3	10·4	7·5	16·0	·23	·3886	·127	58·3%	58·4%
30·87	5·01	6·138	178	8	3	9·6	8·5	16·0	·23	·3803	·120	60·6%	61·5%
30·87	5·01	5·898	178	8	3	9·0	9·5	15·8	·22	·3710	·108	65·3%	62·1%
30·87	5·01	5·645	178	8	3	8·4	10·5	15·3	·22	·3618	·100	69·0%	64·9%
30·37	5·01	5·166	178	8	3	7·6	11·5	14·0	·21	·3578	·93	72·0%	66·6%
30·87	5·01	4·790	178	8	3	6·8	12·5	13·8	·21	·3452	·084	78·0%	70·6%
30·87	5·01	4·389	178	8	3	6·2	13·5	13·5	·21	·3432	·083	80·0%	75·8%
30·87	5·01	4·003	178	8	3	5·6	14·5	13·0	·20	·3402	·08	84·0%	80·9%
30·87	5·01	3·499	178	8	3	4·9	15·5	13·0	·19	·3406	·025	99·0%	91·9%

Reduction of Meter Errors in Measurement of Compressor Discharge, when Incurred by Velocity Pulsation.

It has been shown that the determination of meter errors in the measurement of compressor discharge may be predicted with reasonable accuracy, when the pressure variation in the discharge reservoir is negligible. This implies that the compressor is discharging into a fairly large system and that no appreciable throttling, other than at the measuring orifice, takes place between the compressor and the main system. It will be readily recognised from a study of the graphs of the functions,

$$\frac{\sqrt{r}\,(1+r)}{2\,(a+\sqrt{r})\,(1-r)} \text{ and } \left\{\frac{(a+1)}{(a+\sqrt{r})} \times \sqrt{\frac{1+r}{2}} - 1\right\} \times 100 \text{ per cent.},$$

on a base of factor, "r," that, where the error is *appreciable*, this error could not be employed as a correction or "rating factor," because, unless the error be small, any small change in C, F, Xa or Q would result in a very large change in the correction factor.

The determination of the error in any particular case and the ability to predict the requisite increase in capacity and/or decrease in orifice size for the reduction to a negligible amount of the meter error are obviously of extreme importance, however.

The following procedure should be adopted in eliminating the meter error by the most economical method :—

1. Determine the error under the existing conditions, by applying formulae Nos. 16 and 18.
2. (*a*) If the meter error is found to be small (*i.e.*, of the order of 1 to 3 per cent.) for the minimum possible value of F, consistent with the maximum possible values of Q and $\frac{P_2}{P_1}$ then a correction factor can be applied, as provided by equation No. 16. The orifice diameter should be reduced to the minimum permitted by the differential range of the meter. If, thereafter, the orifice is changed, the rating factor should be corrected accordingly ; or

2. (*b*) If the meter error is found to be large, the requisite increase of capacity and/or throttling depend upon the differential range of the meter. When this is known, the additional capacity can be determined from equating :—

Value of $\frac{1{\cdot}3036\ CFXA}{T\sqrt{Q}}$		For value of "a."
23	.....	0·35
24	.....	0·30
26	.....	0·20
31	.....	0·10

If the required capacity can be obtained by removing the meter to some point conveniently remote, or if the capital cost of the additional capacity is not prohibitive, a reduction of error to the order of 1 to ½ per cent. can be obtained. If necessary, a correction factor, based upon Equation No. 16, can be applied to rate the meter. Tests show that, by this means, an orifice meter, measuring discharge gas from a compressor, can be rated with remarkable accuracy; or

2. (*c*) If the additive effect of (*a*) the permissible increase of throttling, concomitant with the differential range of the meter, and (*b*) the maximum possible economic increase of capacity is not sufficient to reduce the error to a suitable degree, the introduction of *another* throttling orifice or device at some convenient point, over 50 diameters upstream from the measuring orifice, will be less expensive and equally effectual. The size of this extra throttling orifice depends upon the degree of throttling which is economically allowable. If we assume that 2·0 lbs./sq. in. throttling is permissible at this throttling device, the required capacity between this throttling orifice and the compressor discharge valves is given by equating:—

$$\frac{1{\cdot}3036\, C_1 F}{Tf\, Q} = \frac{25}{55{\cdot}5} \qquad \ldots\ldots (24)$$

or $$C_1 = 0{\cdot}3456\, \frac{Tf\, Q}{F}.$$

This method is only practicable if Q is fairly constant. The drop in pressure across this orifice varies as Q^2. Consequently, if the station, whose discharge is to be measured, consists of more than one compressor, a fixed orifice could not be used conveniently. For a large station it would be more economical to introduce the requisite capacity or a differential control valve upstream of the discharge meter.

Reduction of Pulsation Errors.

2. *Measurement of Compressor Intake.*—The equations developed under measurement of Compressor Discharge (i.e., Equations Nos. 16 and 18), are also applicable to the measurement of compressor intake, it being assumed that the change in pressure in the intake reservoir is negligible. If the pressure in the reservoir is small, the ratio of pressure change to absolute pressure may be appreciable, but the pressure upstream of the orifice may be assumed constant, provided that no appreciable throttling takes place upstream of the measuring orifice, in the vicinity of the station, and that the ratio

of maximum differential in inches water to the absolute pressure at the meter in pounds per square inch is not greater than 0·5.

The assumption that the pressure upstream of the measuring orifice is constant implies that all successive storage and release from storage must take place in the inlet reservoir. Hence Equation No. 18, which is based on similar premises, can be applied. The values of factor "a" are different from those for measurement of compressor discharge, however.

The value of "a" for measurement of intake to a compressor is mainly dependent upon the value of the ratio

$$\frac{\text{L.P. Capacity}}{\text{Displacement}} = \left\{1+\text{Rc}-\text{Rc}\times\left(\frac{P_2}{P_1}\right)^{1/1\cdot26}\right\}$$

where $\text{Rc} = \dfrac{\text{Clearance Volume}}{\text{Displacement Volume}}$ ..... (25)

The actual period of intake is less than that represented by the L.P. capacity, due to the intake valves not opening until the pressure in the cylinder is appreciably less than the pressure in the intake reservoir.

The ratio of volume in cylinder at point of opening of intake valves to the theoretical volume given by

$$\left\{1+\text{Rc}-\text{Rc}\left(\frac{P_2}{P_1}\right)^{\cdot794}\right\}$$

is approximately 0·96—0·97 in practice.

The equivalent period of uniform flow, with maximum differential of the flowing period, is less than that of the actual period of intake, due to the variation in piston speed throughout the period. (Curve of rate of intake *at the pressure in the cylinder* is approximately "simple harmonic.")

The mean value of "a" can consequently be calculated by modifying the curve of piston speed on a base of time to show the rate of intake, measured at standard pressure and temperature. These values closely correspond to experimentally determined values.

For all probable values of "a" the error is less than 2 per cent. if $\dfrac{1\cdot3036\ \text{C F Xa}}{\text{T f Q}}$ is greater than 1·3.

For reduction of meter error to less than 0·5 per cent., $\dfrac{1\cdot3036\ \text{C F Xa}}{\text{T f Q}}$ should be greater than 3·0.

A curve of experimentally determined values of "a" for atmospheric pressure intake is attached, showing also theoretical values, for atmospheric pressure in the intake reservoir.

EXCERPT FROM TESTS.

Measurement with "Full Flow Connections" of Compressor Intake.

"C," "Tf," "F" Constant. "Q" Fairly Constant. "XA" Variable.

"C" Capacity of Intake Reservoir in Cu. Ft.	"F" Frequency of Pulsation in Cycles per Sec.	"Q" Mean rate of Flow in Cu. Ft. at N.T.P. 14·4 lbs. and 60° F) per Sec.	"Tf" Flowing Temp. in Degrees Fahrenheit (Mean).	Diameters.		"XA" Differential recorded by Meter, with Full Flow Connections, in Inches of Water.	Pressures.		Value of Factor "a." $= \frac{\sqrt{r(1+r)}}{2(a+\sqrt{r})(1-r)}$	Value of $\frac{1{\cdot}3036\ CFXA.}{TfQ}$	Value of Calculated Meter error % $= \left\{\frac{(a+1)}{(a+\sqrt{r})}\sqrt{\frac{1+r}{2}}-1\right\}\times 100$	Value of actual Error %
				Internal of Pipe in Inches.	Orifice in Inches.		Intake in Inches of Mercury Vacuum.	Discharge in Pounds per Sq. Inch. Gauge.				
14·70	5·01	7·535	97	6	4·0	2·3	1	10	1·41	0·0526	12·5%	12·2
14·70	5·01	7·820	97	6	4·0	2·4	0	10	1·41	0·0529	12·5%	12·0
14·70	5·01	8·247	97	6	3·5	5·0	0	13	1·40	0·1045	3·5%	3·5
14·70	5·01	7·900	97	6	3·0	10·0	5	13	1·40	0·2182	0·0%	0·5

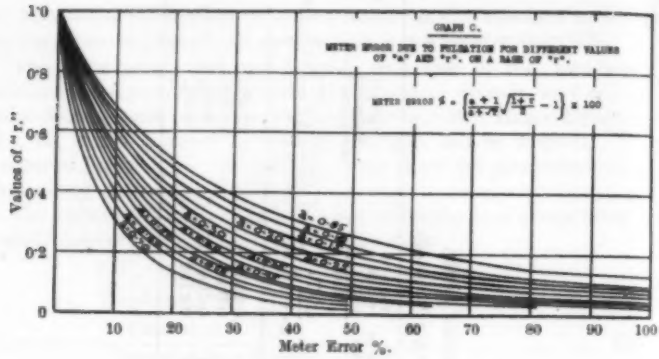

GRAPH C.
METER ERROR DUE TO PULSATION FOR DIFFERENT VALUES OF "a" AND "r". ON A BASE OF "r".
METER ERROR % = $\left(\frac{a+1}{a+\sqrt{r}}\sqrt{\frac{1+r}{2}}-1\right)\times 100$
Values of "r."
Meter Error %.
a = 0·85
a = 0·90
a = 0·95
a = 1·0
a = 1·25
a = 1·50
a = 2·0
a = 3·0
a = 5·0

Table of Calculated Values of the Meter Error

$$\left\{\frac{a+1}{a+\sqrt{r}}\sqrt{\frac{1+r}{2}}-1\right\}\times 100\%$$

Due to Velocity Pulsation, for Different Values of the Factors, "a" and "r"—for Intake Measurement.

Error in %.

Values of "a."	Values of "r."								
—	0·95	0·90	0·85	0·80	0·60	0·40	0·20	0·10	0·05
1·0	0·0	0·0	+0·1	+0·15	+0·80	+ 2·5	+ 7·0	+12·7	+18·4
1·25	—0·16	—0·26	—0·39	—0·46	—0·60	0·0	+ 2·7	+ 6·5	+10·6
1·50	—0·26	—0·51	—0·76	—0·96	—1·69	— 1·91	— 0·55	+ 2·1	+ 5·1
2·0	—0·44	—0·83	—1·28	—1·69	—3·28	— 4·65	— 5·03	— 3·93	— 2·79
3·0	—0·62	—1·26	—1· 1	—2·55	—5·21	— 7·85	—10·11	—10·52	—10·11
4·0	—0·76	—1·51	—2· 2	—3·08	—6·33	— 9·69	—12·90	—14·08	—14·22
5·0	—0·85	—1·69	—2·55	—3·42	—7·06	—10·85	—14·67	—16·29	—16·76
0·90	0·1	0·2	0·2	0·4	1·5	3·8	9·2	15·9	22·6

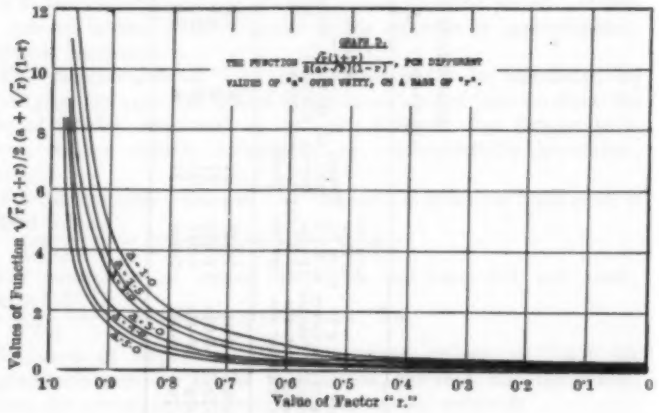

GRAPH D.
THE FUNCTION $\frac{\sqrt{r}(1+r)}{2(a+\sqrt{r})(1-r)}$, FOR DIFFERENT VALUES OF "a" OVER UNITY, ON A BASE OF "r".
Values of Function $\sqrt{r}(1+r)/2(a+\sqrt{r})(1-r)$
Value of Factor "r."
a = 1·0
a = 1·25
a = 1·5
a = 2·0
a = 3·0
a = 5·0

Table of Values of the Function

$$\frac{\sqrt{r}\,(1+r)}{2\,(a+\sqrt{r})\,(1-r)}$$

Values of "a."	Values of "r."							
—	0·95	0·90	0·85	0·80	0·60	0·40	0·20	0·10
1·0	9·623	4·625	2·959	2·127	0·8728	0·4519	0·2318	0·1309
1·25	8·541	4·109	2·617	1·877	0·7649	0·3918	0·1976	0·1100
1·50	7·681	3·681	2·347	1·681	0·6810	0·3459	0·1723	0·0949
2·0	6·389	3·057	1·945	1·559	0·5582	0·2802	0·1371	0·0744
3·0	4·780	2·282	1·450	1·034	0·4103	0·2031	0·0996	0·0519
4·0	3·820	1·822	1·155	0·8224	0·3243	0·1592	0·0754	0·0399
5·0	3·181	1·515	0·9603	0·6829	0·2681	0·1310	0·0616	0·0324
0·90	10·14	4·856	3·120	2·243	0·9249	0·4814	0·2490	0·1590

Reduction of Pulsation Error in Meters.

3. *Measurement of gas flows affected by chattering check valves, undamped diaphragm regulators, fuel burners, etc.*—In general the wave form of flow may be regarded as a full harmonic curve, superimposed upon a uniform rate in cases of gas flows affected by non-return valves, undamped regulators, etc., provided that no pulsations, due to other cause, exist. Consequently, if based upon premises similar to those adopted in determining the criterion for compressor pulsation, it can be shown by similar methods :—

(*a*) That the meter error per cent. is equal to

$$\left\{\frac{2\sqrt{\frac{1+r}{2}}}{1+\sqrt{r}}-1\right\} 100 \text{ per cent. (i.e., "a" has the value, unity)} \quad \ldots\ldots\ldots\ldots\ldots \quad (28)$$

and (*b*) that the function

$$\frac{1{\cdot}3036\,C\,F\,XA}{TfQ} = \frac{{\cdot}35\,\sqrt{r}(1+r)}{(1+\sqrt{r})\,(1-r)} \quad \ldots\ldots\ldots\ldots\ldots \quad (29)$$

if it be assumed that the non-return valve or regulator *closes* for an instant at the termination of each complete cycle.

Value of "r"	0·95	0·90	0·85	0·80	0·60	0·40	0·20	0·10
Value of the meter error %	0	0	0·1	0·15	0·8	2·5	7·0	12·7
Values of function— $\frac{1{\cdot}3036\,CFXA}{TfQ}$	6·736	3·238	2·072	1·489	0·611	0·316	0·163	0·092

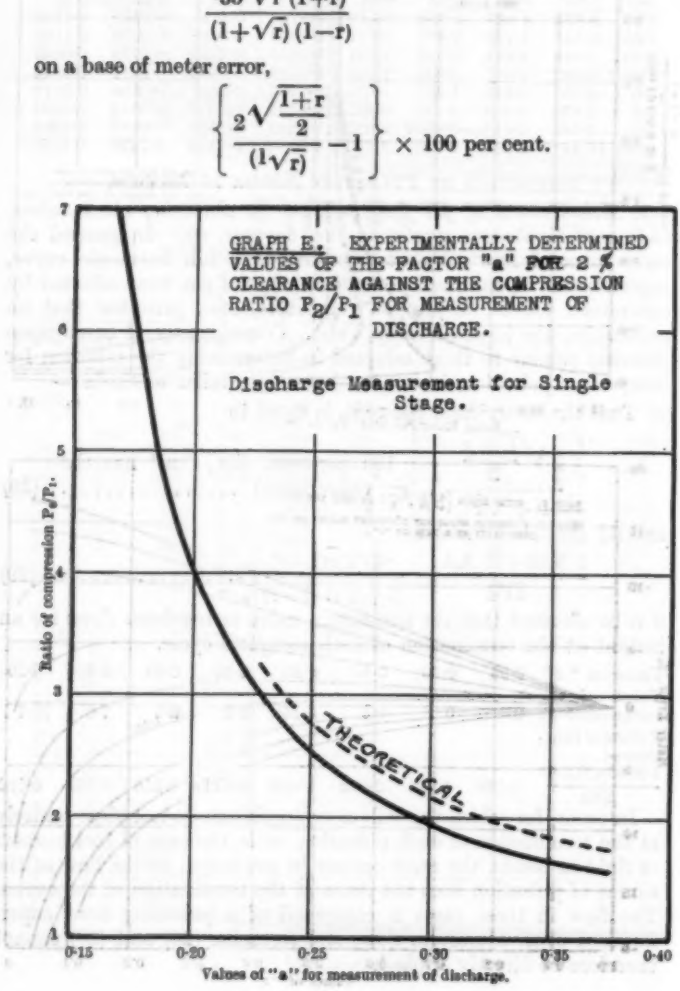
In cases, for which the valves or regulators do not close entirely at the termination of each pulsation, or in the case of fuel burners or fluid in bends, the error cannot be predicted, as the flow at the source of pulsation does not cease at the termination of the cycles. The flow in these cases is composed of a pulsating flow, superimposed upon a uniform flow, and formulae (28) and (29) cannot therefore be directly applied.

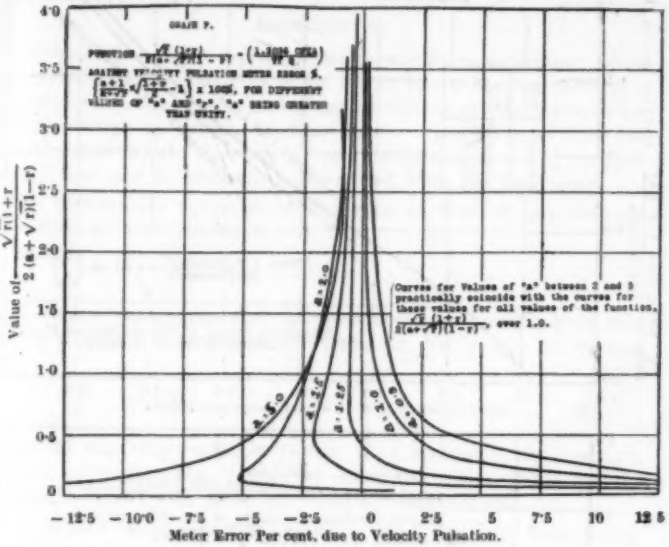
The existing error can be determined by throttling an intermediate valve between the meter and the source of pulsation, and the requisite increase in the product, $C \times Xa$, determined from the curve of the function,

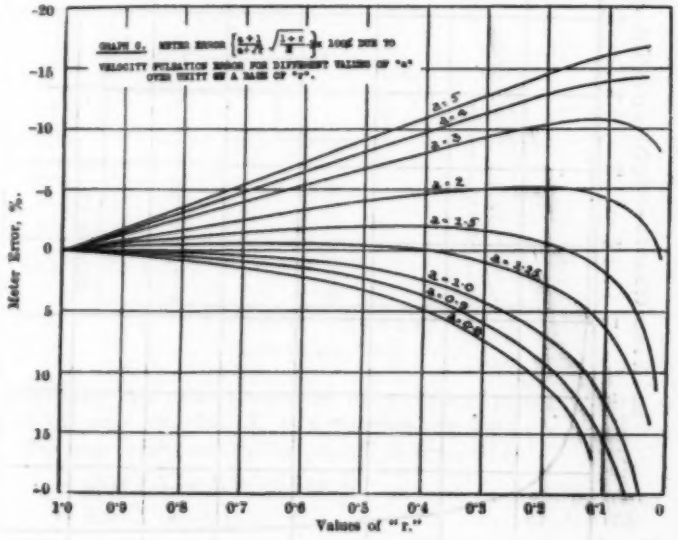
$$\frac{\cdot 35\sqrt{r}\,(1+r)}{(1+\sqrt{r})\,(1-r)}$$

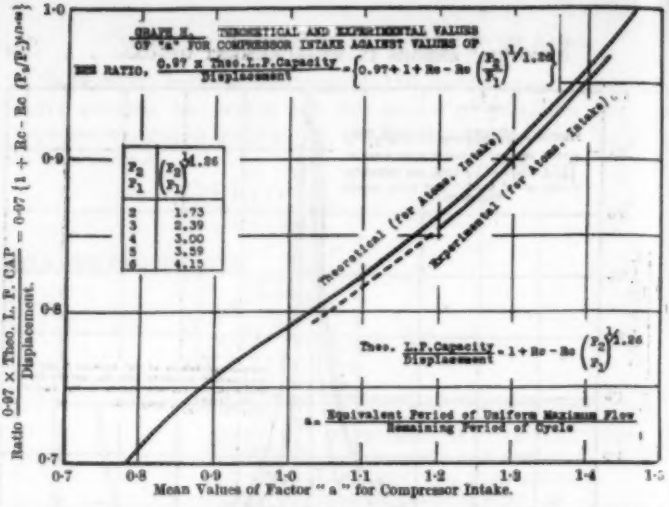
on a base of meter error,

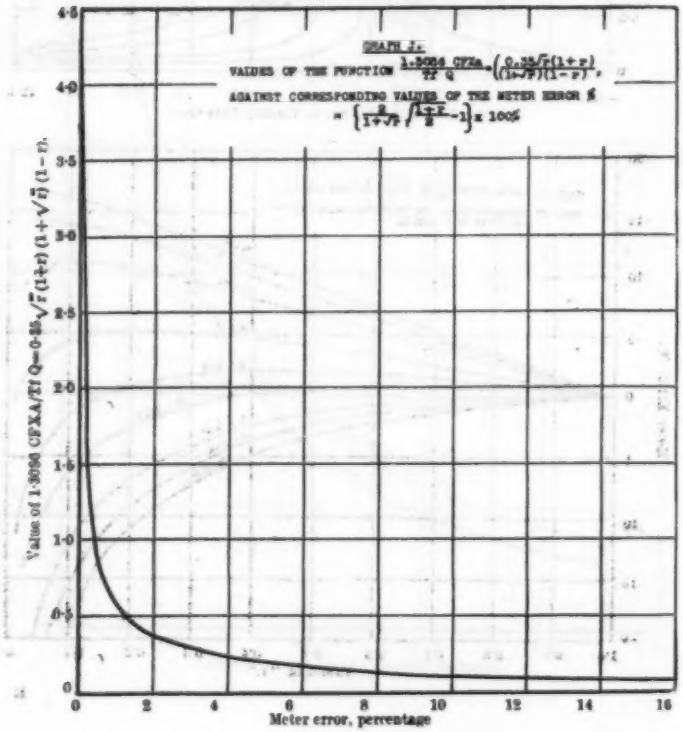
$$\left\{\frac{2\sqrt{\frac{1+r}{2}}}{(1\sqrt{r})} - 1\right\} \times 100 \text{ per cent.}$$




GRAPH F.
Value of $\frac{\sqrt{r}(1+r)}{2(a+\sqrt{r})(1-r)}$
4·0
3·5
3·0
2·5
2·0
1·5
1·0
0·5
0
a = 5·0
a = 3·5
a = 3·0
a = 2·5
a = 2·0
a = 1·5
Curves for Values of "a" between 2 and 5 practically coincide with the curves for these values for all values of the function, $\frac{\sqrt{r}(1+r)}{2(a+\sqrt{r})(1-r)}$, over 1.0.
−12·5 −10·0 −7·5 −5 −2·5 0 2·5 5 7·5 10 12·5
Meter Error Per cent. due to Velocity Pulsation.


GRAPH G.
VELOCITY PULSATION ERROR FOR DIFFERENT VALUES OF "a" OVER UNITY ON A BASE OF "r".
Meter Error, %.
-20
-15
-10
-5
0
5
10
15
-0
a = 5
a = 4
a = 3
a = 2
a = 1·5
a = 1·25
a = 1·0
a = 0·9
a = 0·8
1·0 0·9 0·8 0·7 0·6 0·5 0·4 0·3 0·2 0·1 0
Values of "r."


GRAPH H.
THEORETICAL AND EXPERIMENTAL VALUES OF "a" FOR COMPRESSOR INTAKE AGAINST VALUES OF
RHS RATIO, 0.97 x Theo. L.P. Capacity / Displacement = {0.97 + 1 + Rc - Rc (P2/P1)^1/1.26}
P2/P1 | (P2/P1)^1/1.26
2 | 1.73
3 | 2.39
4 | 3.00
5 | 3.59
6 | 4.12
Theoretical (for Atmos. Intake)
Experimental (for Atmos. Intake)
Theo. L.P. Capacity / Displacement = 1 + Rc - Rc (P2/P1)^1/1.26
a = Equivalent Period of Uniform Maximum Flow / Remaining Period of Cycle
Ratio 0.97 x Theo. L. P. CAP / Displacement = 0.97 {1 + Rc - Rc (P2/P1)^1/1.26}
1.0
0.9
0.8
0.7
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
Mean Values of Factor " a " for Compressor Intake.


GRAPH J.
VALUES OF THE FUNCTION 1.3086 CFXA/Ti Q = 0.85 √r (1+p) (1+√r) (1-p),
AGAINST CORRESPONDING VALUES OF THE METER ERROR δ
= {r/(1+√r) / (1+p)/2 - 1} x 100%
Value of 1.3086 CFXA/Ti Q=0.85√r(1+p)(1+√r)(1-p).
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
0
2
4
6
8
10
12
14
16
Meter error, percentage

Appendix 1.

Determination of the degree of inaccuracy in measurement, which is incurred by the substitution of the square root of the true mean of a variable for the mean square root of that variable in the integral equation of flow through an orifice, in cases where: (A) *There is only one variable, and* (B) *the duration of each successive period of uniform rate of flow can be accurately determined from the flow chart.*

The differential equation of the rate of flow of gas through an orifice at any instant is:—

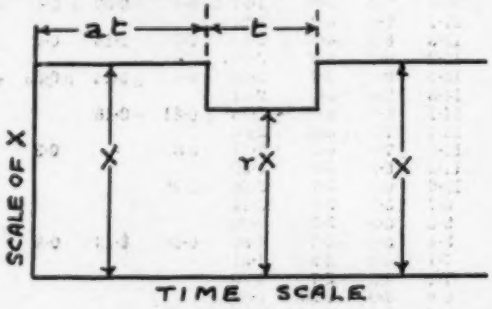
$$\frac{dQ}{dt} = C\sqrt{\frac{H.P.}{G.T.}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

If, therefore, we assume that only one factor on the right hand side of this equation is variable, the equation No. 1 can be written thus:—

$$\frac{dQ}{dt} = K\sqrt{X} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

where X, the only variable factor, may represent the absolute pressure in the line, the differential across the orifice, or the inverse of specific gravity or absolute flowing temperature.

Let us now determine the quantity, "Q," the total flow during the period of measurement, t+at, in the simple hypothetical case shown on Flow Chart No. 1



Flow Chart No. 1.

Integrating this chart accurately, for successive periods, during which the only variable, X, is a constant, we have:—

The true total quantity, Q, passing in time, t+at,

$$= (Kat\sqrt{X} + Kt\sqrt{rX}) \text{ cu. ft.},$$

$$= Kt\sqrt{X}\,(a+\sqrt{r}) \text{ cu. ft.} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

The true mean value of X, during the period, t+at :—

$$= \frac{Xat+rXt}{at+t} = \frac{X\ (a+r)}{(a+1)} \text{ units} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

∴ The approximate total quantity, "Q," passing in true, t+at, substituting the square root of the true mean of X for the mean square root :—

$$= Kt\ (a+1)\sqrt{\frac{X\ (a+r)}{(a+1)}} \text{ cu. ft.} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (5)a$$

$$= Kt\sqrt{X}\ \sqrt{(a+r)\ (a+1)} \text{ cu. ft.} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

∴ The ratio of error :—

$$= \frac{\text{The approximate total quantity, } Q_2,\ r\sqrt{(a+r)\ (a+1)}}{\text{The true total quantity, } Q\qquad\qquad (a+\sqrt{r})} \quad \ldots\ldots\ldots\ldots \quad (6)$$

∴ The percentage error in measurement, incurred by substituting the square root of the true mean square root of :—

$$X_1 = \left\{ \frac{\sqrt{(a+r)\ (a+1)} - (a+\sqrt{r})}{(a+\sqrt{r})} \right\} \times 100\%$$

Percentage Error in Measurement.

TABLE No. 1.

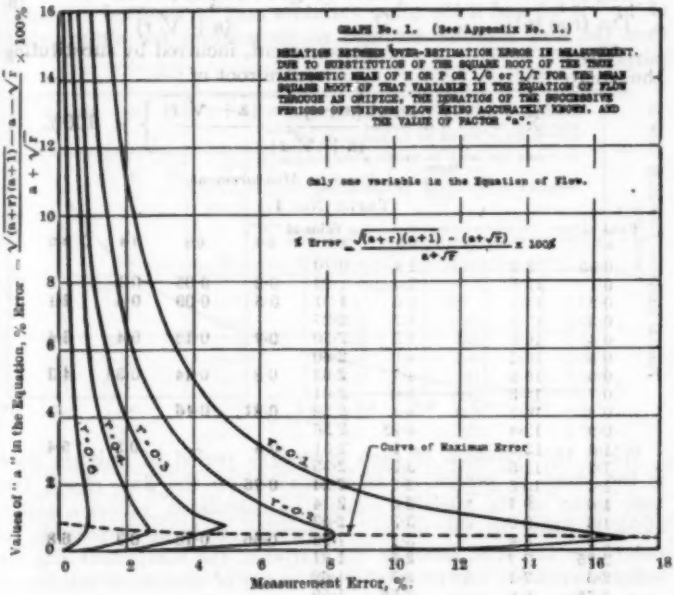
Value of "a."	Value of "r." 0·1	0·2	0·3	0·4	0·6	0·8	1·4	4·0
0·05	8·4	3·0	1·4	0·70				
0·1	12·5	4·4	2·4	1·23	0·3	0·06	0·1	
0·2	16·2	7·0	3·6	1·91	0·5	0·09	0·4	2·1
0·3	17·1	7·9	4·2	2·27				
0·4	16·8	8·2	4·5	2·50	0·7	0·13	0·4	3·4
0·5	16·2	8·2	4·6	2·60				
0·6	15·5	8·1	4·7	2·63	0·8	0·14	0·38	4·3
0·7	14·8	7·8	5·0	2·61				
0·8	14·1	7·6	4·4	2·58	0·81	0·16		
0·9	13·4	7·3	4·25	2·56				
1·0	12·5	7·1	4·1	2·51	0·8	—	0·3	5·4
1·2	11·5	6·5	3·9	2·39				
1·4	10·6	6·1	3·7	2·24	0·76			
1·6	9·7	5·7	3·5	2·14				
1·8	9·0	5·3	3·3	2·03				
2·0	8·4	5·0	3·1	1·92	0·66	0·13	0·3	6·8
2·25	7·7	4·6	2·9	1·81				
2·5	7·1	4·3	2·7	1·69				
2·75	6·6	4·0	2·65	1·59				
3·0	6·2	3·8	2·4	1·53				
3·5	5·5	3·4	2·1	1·38	0·53			
4·0	4·9	3·1	2·0	1·27	—	—	0·2	5·4
5·0	4·1	2·6	1·7	1·04	0·4			
6·5	3·2	2·0	1·3	0·86				
8·0	2·7	1·7	1·1	0·69	0·3	0·05		
10·0	2·2	1·5	0·87	0·52				
12·5	1·8	1·1	0·74	0·47	0·17			
15·0	1·5	1·0	0·64	0·36				
17·5	1·3	0·8	0·53	0·35				
20·0	1·2	0·7	0·43	0·32	0·10			

The results obtained apply when any one of the factors, H,P, $\frac{1}{G}$, $\frac{1}{T}$, vary, the others remaining constant, during the period of measurement.

From the graph (Graph No. 1) the maximum errors occur for varying values of "r" when :—

"a" is approximately 0·5.

The curve of maximum error is shown on the graph. The maximum error in measurement does not exceed over 1 per cent. over-estimation, if "r" is greater than 0·7. Hence, since the variation in the inverses of G and T rarely result in "r" having a value less than 0·8 during normal periods of measurement (24


GRAPH No. 1. (See Appendix No. 1.)
RELATION BETWEEN OVER-ESTIMATION ERROR IN MEASUREMENT, DUE TO SUBSTITUTION OF THE SQUARE ROOT OF THE TRUE ARITHMETIC MEAN OF H OR P OR 1/G or 1/T FOR THE MEAN SQUARE ROOT OF THAT VARIABLE IN THE EQUATION OF FLOW THROUGH AN ORIFICE, THE DURATION OF THE SUCCESSIVE PERIODS OF UNIFORM FLOW BEING ACCURATELY KNOWN, AND THE VALUE OF FACTOR "a".
Only one variable in the Equation of Flow.
% Error $= \frac{\sqrt{(a+r)(a+1)} - (a+\sqrt{r})}{a+\sqrt{r}} \times 100\%$
Values of "a" in the Equation, % Error $= \frac{\sqrt{(a+r)(a+1)} - a - \sqrt{r}}{a+\sqrt{r}} \times 100\%$
r = 0·6
r = 0·4
r = 0·3
r = 0·1
r = 0·2
Curve of Maximum Error
Measurement Error, %.

hours), the per cent. measurement error, incurred by employing the square root of the mean value of temperatures and specific gravity for the mean square root, may be considered as extremely small, *if* the other factors do not vary appreciably.

It should be noted that the measurement errors are based on the assumption, that the duration of each period of regular flow is known.

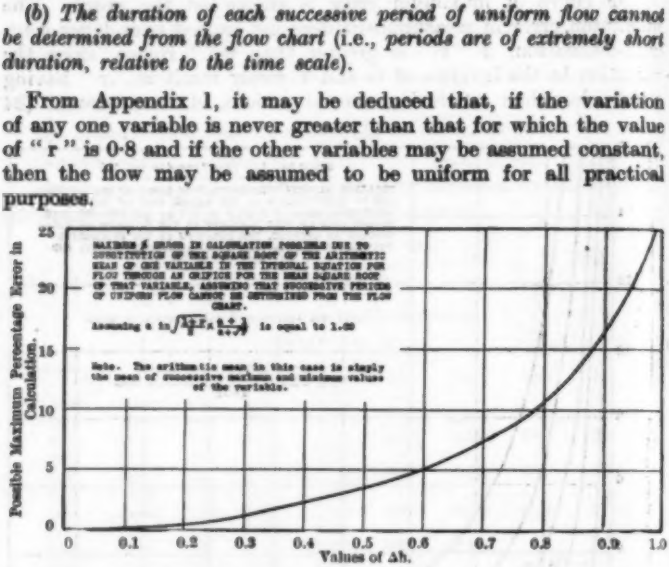
Appendix 2.

Determination of the degree of inaccuracy in measurement, which is incurred by substituting the square root of the arithmetic mean of successive maximum and minimum values of a variable for the mean square root of that variable in the integral equation of flow through an orifice, in cases where:—

(a) *There is only one variable, and*

(b) *The duration of each successive period of uniform flow cannot be determined from the flow chart* (i.e., *periods are of extremely short duration, relative to the time scale*).

From Appendix 1, it may be deduced that, if the variation of any one variable is never greater than that for which the value of "r" is 0·8 and if the other variables may be assumed constant, then the flow may be assumed to be uniform for all practical purposes.



When the duration of each successive period of uniform flow is too short to permit of determination on the flow chart, the true mean of the variable cannot be calculated, unless a faster clock is fitted to the meter. Otherwise, it being impossible to determine the true mean of the variable, the computant has no other alternative but to employ the mean of successive maximum and minimum values of the variable for periods during which this mean is apparently uniform.

In the hypothetical case shown in Appendix 1, the computant selects the mean of successive maximum and minimum values, which is:—

$$\frac{X+rX}{2} = \frac{X\ (1+r)}{2} \text{ units} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (7)$$

The approximate integration of $Kt \int_{o}^{at+t} \sqrt{X}\, dt$ then becomes :—

$$K\,(at+t)\sqrt{\frac{X\,(1+r)}{2}} \text{ cu. ft.} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (8)$$

$$= Kt\sqrt{X}\cdot(a+1)\cdot\sqrt{\frac{1+r}{2}} \text{ cu. ft.} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (9)$$

The true total quantity passing in time, at+t, is given by equation No. 3 in Appendix 1 :—

"Q," the true total quantity $= Kt\sqrt{X}\,(a+\sqrt{r})$ cu. ft. .... (10)

∴ The error ratio,

$$\frac{\text{the approximate total quantity, } Q_1}{\text{the true total quantity, } Q} = \frac{(a+1)\sqrt{\frac{1+r}{2}}}{(a+\sqrt{r})} \quad \ldots\ldots \quad (11)$$

The per cent. error in measurement=

$$\frac{\left\{\sqrt{\frac{1+r}{2}}\cdot(a+1)-(a+\sqrt{r})\right\}}{(a+\sqrt{r})}\cdot 100\ \% \quad \ldots\ldots\ldots\ldots \quad (12)$$

TABLE No. II.

Percentage Error in Measurement (see Equation (12)).

Values of "a."	Values of "r." 0·2	0·4	0·6	0·8
0·2	43·6	20·6	10·1	4·0
0·4	27·9	13·4	6·5	2·6
0·5	22·7	10·9	5·2	2·3
0·6	18·4	8·6	4·1	1·6
0·8	11·8	5·2	2·2	—
1·0	7·0	2·5	0·8	0·1
2·0	—5·1	—4·6	—3·3	—1·7

As one would naturally expect, the errors in this case are very much greater than those in the Case I., in which the mean is more accurately determined, due to the fact that the period of each successive period of uniform flow is known in Case I.

It should be noted from Table No. II. and Graph No. 2, that :—

1. the smaller the value of "a" the greater is the positive error, "r" being constant (assuming "a" less than 1·0);
2. the smaller the value of "r" the greater is the error, "a" being constant; and
3. for values of "a" over 1·0 the error becomes an under estimation. In general practice vibrating flow is a compound of the hypothetical cases assumed in Appendices 1 and 2. The

possible error for any actual case, if the periods of integration employed by the computant are known, can be easily ascertained by multiplying the errors ratios given by Tables Nos. I and II.

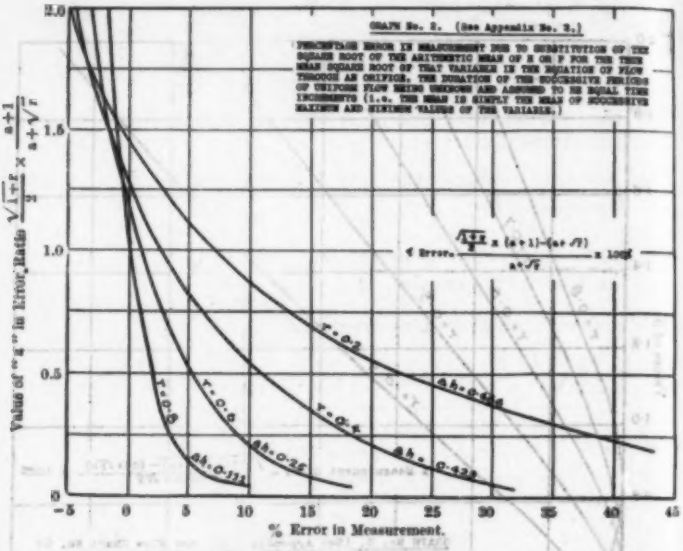
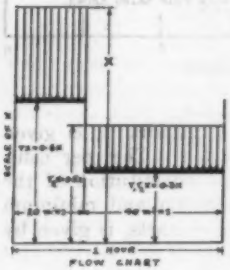
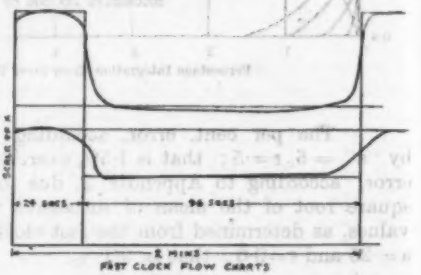


CHART No. 2. (See Appendix No. 2.)
PERCENTAGE ERROR IN MEASUREMENT DUE TO SUBSTITUTION OF THE SQUARE ROOT OF THE ARITHMETIC MEAN OF R OR P FOR THE TRUE MEAN SQUARE ROOT OF THAT VARIABLE IN THE EQUATION OF FLOW THROUGH AN ORIFICE. THE DURATION OF THE SUCCESSIVE PERIODS OF UNIFORM FLOW BEING KNOWN AND ASSUMED TO BE EQUAL TIME INCREMENTS (i.e. THE MEAN IS SIMPLY THE MEAN OF SUCCESSIVE MAXIMUM AND MINIMUM VALUES OF THE VARIABLE.)
Value of "q" in Error Ratio
% Error in Measurement.
r = 0·2
r = 0·4
r = 0·6
r = 0·8
Ab = 0·111
Ab = 0·25
Ab = 0·429
Ab = 0·432

In order to demonstrate this clearly, let us take the following simple compound example shown on charts Nos. 1A & 1B.



No. 1A.

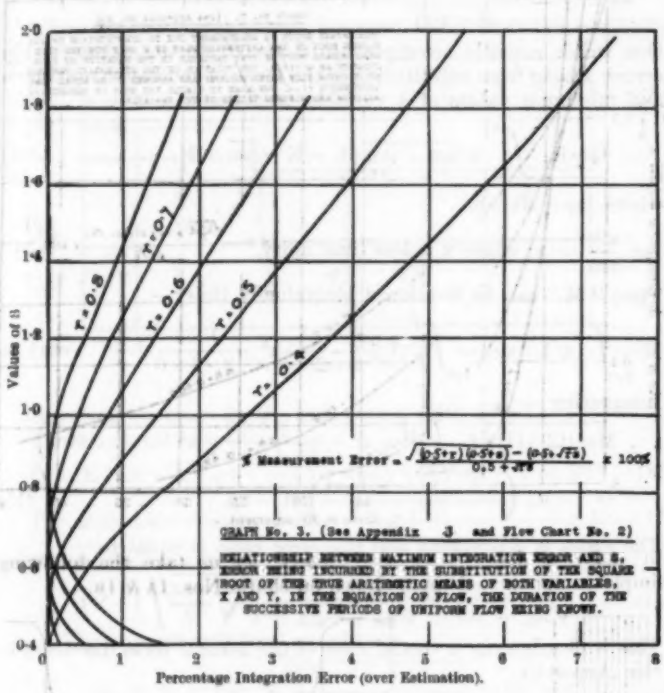


No. 1B.

Let us assume that $r_1 = 0{\cdot}6$ and $r_2 = 0{\cdot}5$. Then the error, incurred by substituting the square root of the true mean of X for the mean

square root, neglecting the error due to vibrating flow, is obtained thus :—

The mean value of X during the first 20 minutes is 0·8 X and during the following 40 minutes is ·4X.


Values of a
Percentage Integration Error (over Estimation).
r=0·8
r=0·7
r=0·6
r=0·5
r=0·4
% Measurement Error = $\frac{\sqrt{(0.5+r)(0.5+a)} - (0.5+\sqrt{ra})}{0.5+\sqrt{ra}} \times 100\%$
GRAPH No. 3. (See Appendix 3 and Flow Chart No. 2)
RELATIONSHIP BETWEEN MAXIMUM INTEGRATION ERROR AND E, ERROR BEING INCURRED BY THE SUBSTITUTION OF THE SQUARE ROOT OF THE TRUE ARITHMETIC MEANS OF BOTH VARIABLES, X AND Y, IN THE EQUATION OF FLOW, THE DURATION OF THE SUCCESSIVE PERIODS OF UNIFORM FLOW BEING KNOWN.

∴ The per cent. error, according to Appendix 1, is given by "a" =·5, r=·5 ; that is 1·5% overestimation. The per cent. error, according to Appendix 2, due to the substitution of the square root of the mean of successive maximum and minimum values, as determined from the fast clock flow charts, is given by a=·25 and r=0·6 ; that is, 9·1 %.

Hence the total error in integration for the period of one hour, due to the substituting of square roots of means for the mean square root of the variable, X, in this example is $\{(1{\cdot}015 \times 1{\cdot}091) - 1\} \times 100\% = 10{\cdot}7\%$.

In the special case for vibrating flow, as described in this Appendix, in which " a " has the value 1·0, the per cent. error in measurement

$$= \frac{\left\{2\sqrt{\frac{1+r}{2}} - (1+\sqrt{r})\right\}}{(1+\sqrt{r})} \times 100\% \quad \ldots\ldots\ldots\ldots\ldots (13)$$

One writer recently attempted to demonstrate the nature of the errors, arising from substitution of the mean of successive maximum and minimum values of a variable, as follows :—

$$Q = K \int_{t_1}^{t_2} \sqrt{hm \pm \Delta h}.dt. = K\sqrt{hm} \times M, \quad \ldots\ldots\ldots\ldots (14)$$

where $hm \pm \Delta h = h$.

Let $\frac{\Delta h}{hm} = x$, where x is less than unity.

Then " M " can be developed binominally thus :—

$$M = \int_{t_1}^{t_2} \sqrt{1 \pm x}.dt = \int_{t_1}^{t_2} \left(1 \pm \frac{x}{2} - \frac{1}{2\times4}x^2 \pm \frac{1\times3}{2\times4\times6}x^3 - \ldots \text{etc.}\right) dt$$

Integrating :—

$$\therefore\ M = (t2 - t1)\left\{1 - \left(\frac{1}{2\times4}x^2 + \frac{1\times3\times5}{2\times4\times6\times8}x^4 + \ldots \text{etc.}\right)\right.$$

$$= \left(\frac{\sqrt{1+x} + \sqrt{1-x}}{2}\right)(t_2 - t_1) \quad \ldots\ldots\ldots\ldots\ldots (15)$$

The series is convergent and the error ratio is equal to :—

$$\frac{2\sqrt{hm}}{\sqrt{h_m + \Delta h} + \sqrt{h_m - \Delta h}} = 2\sqrt{\frac{1+r}{2}} \Big/ 1+\sqrt{r}$$

This is clearly only a special case of the general form discussed in this Appendix.

Appendix 3.

Determination of the degree of inaccuracy of measurement, which is incurred by substituting the square roots of the true means for the mean square roots of two variables in the integral equation of flow through an orifice in cases where :—

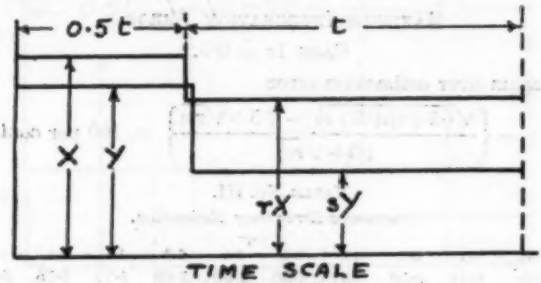
(a) There are only two variables, and

(b) The duration of each successive period of uniform flow can be accurately determined on the flow chart.

As in the hypothetical case considered in Appendix No. 1, in which there is only one variable, it has been shown that, if the duration of the successive periods of uniform flow are known, the maximum

measurement error occurs when " a " is approximately 0·5 (see Graph No. 1). It is assumed in this case that the maximum error incurred by substituting the square roots of the time arithmetic means for the mean square roots of two variables, will occur when " a " = 0·5 in both cases.

There are two distinct cases, however, which meet this condition. The first is shown in Chart No. 2



Flow Chart No. 2.

Integrating the chart for the time period, 1·5 t, we get :—

The true total quantity of gas,

$$Q = K\left\{\cdot 5t\sqrt{XY} + t\sqrt{rsXY}\right\} = Kt\sqrt{XY}\,(\cdot 5 + \sqrt{rs})\ FT^3 \quad .. (16)$$

The arithmetic average of $X = \dfrac{\cdot 5t + trX}{1\cdot 5t} = \dfrac{(\cdot 5 + r)}{1\cdot 5} \times X$ .. (17)

The arithmetic average of factor,

$$Y = \frac{\cdot 5tY + tsY}{1\cdot 5t} = \frac{(\cdot 5 + s)}{1\cdot 5} \times Y \quad \ldots\ldots\ldots\ldots (18)$$

∴ The approximate total quantity

$$Q_1 = K \times 1\cdot 5t \sqrt{\frac{XY\,(\cdot 5+r)\,(\cdot 5+s)}{1\cdot 5^2}} \text{ cubic feet}$$

$$= Kt\sqrt{XY} \times \sqrt{(\cdot 5+r)\,(\cdot 5+s)} \text{ cubic feet} \quad \ldots\ldots (19)$$

∴ The Ratio, $\dfrac{\text{The Approximate Total quantity, } Q_1}{\text{The true Total quantity, } Q}$

$$= \frac{Kt\sqrt{XY} \times \sqrt{(\cdot 5+r)\,(\cdot 5+s)}}{Kt\sqrt{XY} \times (\cdot 5 + \sqrt{rs})}$$

$$= \frac{\sqrt{(\cdot 5+r)\,(\cdot 5+s)}}{(\cdot 5 + \sqrt{rs})} \quad \ldots\ldots\ldots\ldots (20)$$

= Max. error ratio.

$\therefore$ The per cent. error in measurement (max.)

$$= \left\{ \frac{\sqrt{(\cdot5+r)\,(\cdot5+s)} - (\cdot5+\sqrt{rs})}{(\cdot5+\sqrt{rs})} \right\} \times 100\% \ldots\ldots (21)$$

This is the error when the two variable factors change in sympathy simultaneously.

Two Factors Variable.

Maximum Integration Error.

Case 1a = 0·5.

Maximum over estimation error

$$= \left\{ \frac{\sqrt{(\cdot5+r)\,(\cdot5+s)} - (\cdot5+\sqrt{rs})}{(\cdot5+\sqrt{rs})} \right\} \times 100 \text{ per cent.}$$

Table No. III.

Percentage Error Over Estimation.

"r."	"S" 0·4	0·5	0·6	0·7	0·8	1·0	1·2	1·4	1·6	1·8
0·4	0·0	0·15	0·50	0·97	1·50	2·60	3·69	4·79	5·75	6·69
0·5	0·15	0·0	0·09	0·35	0·68	1·50	2·28	3·10	3·93	4·68
0·6	0·50	0·09	0·0	0·08	0·24	0·8	1·40	2·06	2·70	3·34
0·7	0·97	0·35	0·08	0·0	0·08	0·45	0·82	1·34	1·85	2·39
0·8	1·50	0·68	0·24	0·08	0·0	0·14	0·5	0·9	1·3	1·7
1·0	2·60	1·50	0·8	0·45	0·14	0·0	—	—	—	—

From the above table it is clearly shown that when the two variables change in sympathy simultaneously the measurement error, due to substitution, is relatively small. For values of "S" over unity, signifying antipathetic change of the variables, the error increases rapidly.

Appendix 4.

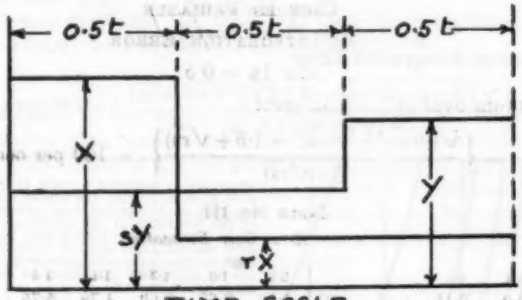
Determination of the possible degree of inaccuracy in measurement, which is incurred by substituting the square roots of the true means for the mean square roots of two variables in the integral equation of flow through an orifice, in cases where (a) *there are only two variables, and* (b) *the duration of each successive period of uniform flow can be accurately determined from the flow chart.*

Case II.

Table No. III shows the maximum probable percentage over estimation error, caused by substituting the square roots of the true means of the two variable factors, "X" and "Y," in the integral flow equation, for the mean square roots of these factors, in the hypothetical case represented by Flow Chart No. 2.

From the graph and the table, it is seen that sympathetic change in "X" and "Y" results in relatively small error, but

that antipathetic change, when the value of "s" is greater than unity and of "r" is less than unity, results in a rapid increase in error with increasing values of "s." Consequently it is necessary to examine the alternative case, as shown by the Flow Chart No. 3, in which maximum probable error will occur.



FLOW CHART No. 3.

Integrating Chart No. 3. correctly (*i.e*, for successive periods, during which both factors, X and Y, are constant) we get :—

The true total quantity, Q, in time 1·5t

$$= K\left\{\cdot 5t\sqrt{XsY} + \cdot 5t\sqrt{rsXY} + \cdot 5t\sqrt{rXY}\right\}$$

$$= \cdot 5Kt\sqrt{XY}\,(\sqrt{s} + \sqrt{r} + \sqrt{rs}) \quad \ldots\ldots (22)$$

Now the arithmetic average of factor, X

$$= \frac{\cdot 5tX + rXt}{1\cdot 5t} = \frac{(\cdot 5 + r)\,X}{1\cdot 5} \quad \ldots\ldots (23)$$

and the arithmetic average of factor, Y

$$= \frac{(\cdot 5 + S)\,Y}{1\cdot 5} \quad \ldots\ldots (24)$$

∴ The approximate total quantity, Q_1, in time, 1·5t

$$= K \times 1\cdot 5t\sqrt{XY} \times \sqrt{\frac{(\cdot 5 + r)\,(\cdot 5 + s)}{1\cdot 5^2}}$$

$$= Kt\sqrt{XY} \times \sqrt{(\cdot 5 + r)\,(\cdot 5 + s)} \quad \ldots\ldots (25)$$

∴ The Ratio, $\dfrac{\text{Approximate Total quantity } Q_1}{\text{The True Total Quantity, } Q}$

$$= \frac{\sqrt{(\cdot 5 + r)\,(\cdot 5 + s)}}{\cdot 5(\sqrt{r} + \sqrt{s} + \sqrt{rs})} \quad \ldots\ldots (26)$$

$\therefore$ The per cent. error in measurement (max.)

$$= \left\{ \frac{\sqrt{(\cdot5+r)\ (\cdot5+s)} - \cdot5\ (\sqrt{r}+\sqrt{s}+\sqrt{rs})}{\cdot5\ (\sqrt{r}+\sqrt{s}+\sqrt{rs})} \right\} \times 100 \text{ per cent.} \quad (27)$$

Two Factors Variable.

Case IIa = 0·5.

(See Flow Chart 3.)

Maximum Integration Error

$$= \left\{ \frac{\sqrt{(\cdot5+r)\ (\cdot5+s)} - \cdot5\ (\sqrt{r}+\sqrt{s}+\sqrt{rs})}{\cdot5\ (\sqrt{r}+\sqrt{s}+\sqrt{rs})} \right\} \times 100 \text{ per cent.}$$

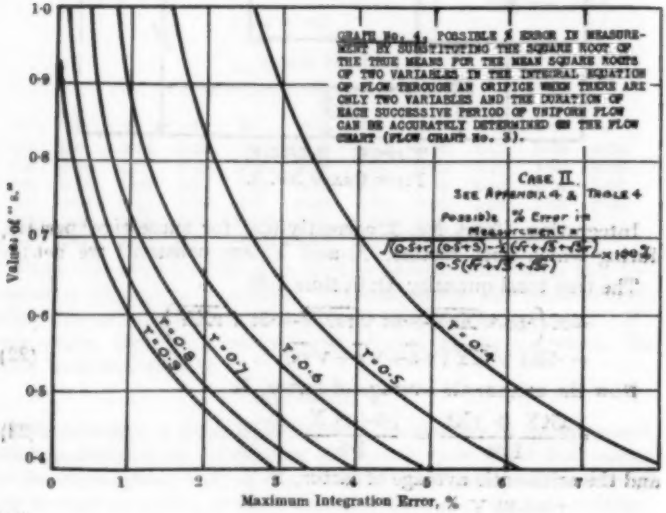

GRAPH No. 4. POSSIBLE % ERROR IN MEASUREMENT BY SUBSTITUTING THE SQUARE ROOT OF THE TRUE MEANS FOR THE MEAN SQUARE ROOTS OF TWO VARIABLES IN THE INTEGRAL EQUATION OF FLOW THROUGH AN ORIFICE WHEN THERE ARE ONLY TWO VARIABLES AND THE DURATION OF EACH SUCCESSIVE PERIOD OF UNIFORM FLOW CAN BE ACCURATELY DETERMINED ON THE FLOW CHART (FLOW CHART No. 3).
CASE II.
SEE APPENDIX 4 & TABLE 4
Possible % Error in Measurement =
Values of "s."
Values of "r."
r=0·9
r=0·8
r=0·7
r=0·6
r=0·5
r=0·4
Maximum Integration Error, %

Table No. IV.

Percentage Error Overestimation.

Values of "r."	Values of "s." 0·4	0·5	0·6	0·7	0·8	0·9
0·4	8·12	6·19	4·90	4·00	3·38	2·93
0·5	6·19	4·48	3·36	2·59	2·08	1·75
0·6	4·90	3·36	2·36	1·70	1·26	0·96
0·7	4·00	2·59	1·70	1·12	0·74	0·54
0·8	3·38	2·08	1·26	0·74	0·43	0·26
0·9	2·93	1·75	0·96	0·54	0·26	0·01

Graph 4 and Table III show that, when the variation of X is inverse to that of Y, the integration error, incurred by substitution of the square root of arithmetic means of the variables for direct

integration, is much greater than when the changes are sympathetic, as shown in Table III. They also show, by comparison with Table I ($s = 0{\cdot}5$), that the error, when only one factor is variable, is much less than when both are variable. The integration error in Case 2 does not exceed 0·5 per cent., if the values of "s" and "r" are never less than 0·8.

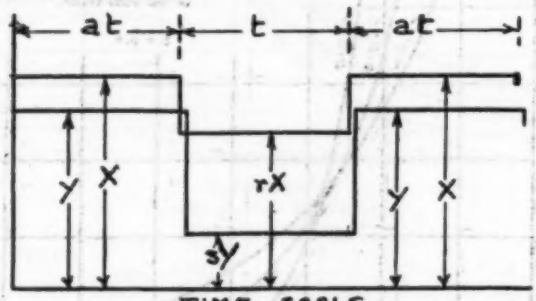
If "s" and "r" are less than 0·8, then the integration error increases rapidly and becomes very serious.

Appendix 5.

Determination of the degree of inaccuracy, which is incurred by the substitution of the square roots of the means of successive maximum and minimum values of two variables in the integral of flow through an orifice, in cases where (a) there are only two variables, (b) the duration of each successive period of uniform rate of flow cannot be determined from the flow chart, due to the time scale being too small and (c) the variables change sympathetically.

The case for one variable is discussed in Appendix 2. In order to determine the latitude permissible in the substitution of the square roots of the means of successive maximum and minimum values of variables in actual practice, the case for two variables should also be examined.

If there are two variables, X and Y, and their time graphs with a fast clock are approximately as shown on Flow Chart No. 4 and if it is assumed that, in the ordinary flow chart, the time scale is too small to permit of determination of the periods of uniform flow, then,



Flow Chart No. 4.

the true total quantity, Q, passing during the period, at+t, is :—

$$Q = K(at\sqrt{XY} + t\sqrt{srXY}) = Kt\sqrt{XY}(a + \sqrt{rs}) \text{ cu. ft.} \quad \ldots \quad (28)$$

The means of the successive maximum and minimum values of

X and Y are $\frac{X\,(1+r)}{2}$ and $\frac{Y\,(1+S)}{2}$ respectively. The duration of each period of uniform flow being unknown, the computant integrates thus :—

$$Q_1, \text{ (the approximate total)} = K\,(at+t)\sqrt{\frac{XY\,(1+r)\,(1+s)}{2\times 2}}$$

$$= Kt\sqrt{XY\,(a+1)}\sqrt{\frac{(1+r)\,(1+s)}{4}} \text{ cu. ft.} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (29)$$

$\therefore$ The Error Ratio, $\frac{\text{Approximate total quantity, } Q_1,}{\text{True total quantity, } Q,}$

$$= \frac{(a+1)\sqrt{(1+r)\,(1+s)}}{2(a+\sqrt{rs})} \quad \ldots\ldots\ldots\ldots\ldots\ldots (30)$$

The Percentage Error in measurement is therefore :—

$$\left\{\frac{(a+1)\sqrt{(1+r)\,(1+s)} - 2\,(a+\sqrt{rs})}{2(a+\sqrt{rs})}\right\} \times 100\% \quad \ldots\ldots \quad (31)$$

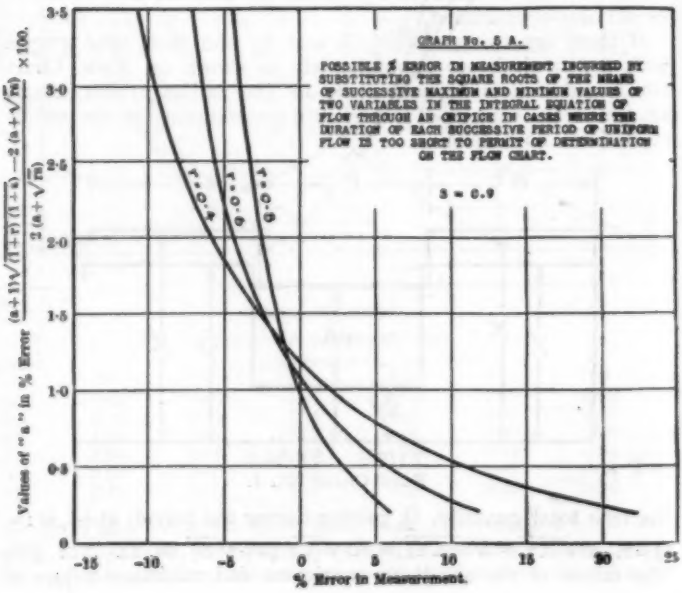

GRAPH No. 5 A.
POSSIBLE % ERROR IN MEASUREMENT INCURRED BY SUBSTITUTING THE SQUARE ROOTS OF THE MEANS OF SUCCESSIVE MAXIMUM AND MINIMUM VALUES OF TWO VARIABLES IN THE INTEGRAL EQUATION OF FLOW THROUGH AN ORIFICE IN CASES WHERE THE DURATION OF EACH SUCCESSIVE PERIOD OF UNIFORM FLOW IS TOO SHORT TO PERMIT OF DETERMINATION ON THE FLOW CHART.
S = 0.9
r = 0.4
r = 0.6
r = 0.8
Values of "a" in % Error $\frac{(a+1)\sqrt{(1+r)\,(1+s)} - 2\,(a+\sqrt{rs})}{2\,(a+\sqrt{rs})} \times 100.$
3·5
3·0
2·5
2·0
1·5
1·0
0·5
0
-15
-10
-5
0
5
10
15
20
25
% Error in Measurement.

TABLE No. Va.

Percentage Error in Measurement.

Value of "s" = 0·9

Values of "a."	Values of "r." 0·4	0·6	0·8
0·2	22·3	11·9	5·9
0·4	14·2	7·5	3·7
0·6	8·7	4·5	2·1
0·8	4·9	2·2	0·9
1·0	2·0	0·5	0·0
1·5	—2·9	—2·5	—1·6
2·0	—5·9	—4·4	—2·6
3·0	—9·4	—6·6	—3·9

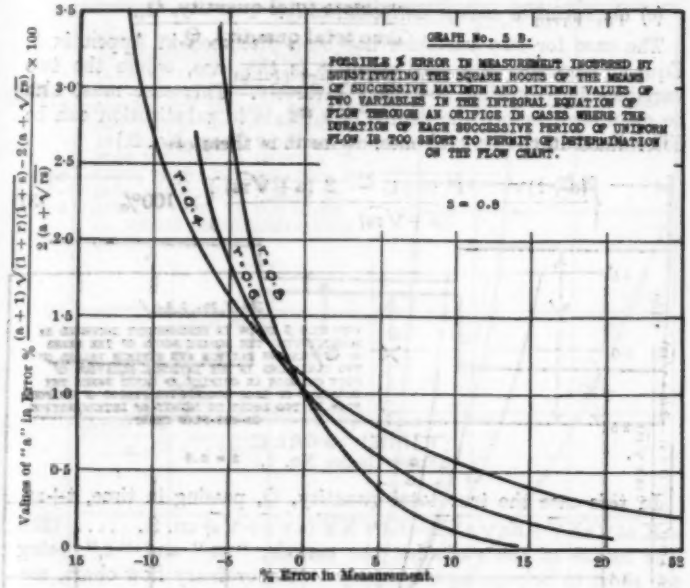

GRAPH No. 5 B.
POSSIBLE % ERROR IN MEASUREMENT INCURRED BY SUBSTITUTING THE SQUARE ROOTS OF THE MEANS OF SUCCESSIVE MAXIMUM AND MINIMUM VALUES OF TWO VARIABLES IN THE INTEGRAL EQUATION OF FLOW THROUGH AN ORIFICE IN CASES WHERE THE DURATION OF EACH SUCCESSIVE PERIOD OF UNIFORM FLOW IS TOO SHORT TO PERMIT OF DETERMINATION ON THE FLOW CHART.
s = 0.8
r = 0.4
r = 0.6
r = 0.8
Values of "a" in Error % $\frac{(a+1)\sqrt{(1+r)(1+s)}-2(a+\sqrt{rs})}{2(a+\sqrt{rs})} \times 100$
3·5
3·0
2·5
2·0
1·5
1·0
0·5
0
15
−10
−5
0
5
10
15
20
32
% Error in Measurement.

TABLE No. Vb.

Percentage Error Measurement.

Value of "s" = 0·8.

Values of "a."	Values of "r." 0·4	0·6	0·8
0·2	24·6	14·0	8·0
0·4	15·1	8·6	5·0
0·6	8·9	5·0	2·9
0·8	4·7	2·3	1·25
1·0	1·4	0·2	0·0
1·5	—4·0	—3·3	—2·0
2·0	—7·2	—5·3	—3·6
3·0	—10·9	—	5·2

Appendix 6.

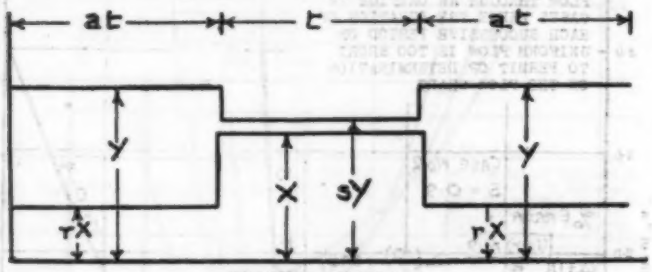
Determination of the degree of inaccuracy in measurement, which is incurred by the substitution of the square roots of the means of successive maximum and minimum values of the two variables for the mean square roots of these variables, in the integral equation of flow through an orifice in cases, where :—

(a) *there are only two variables,*

(b) *the duration of each successive period of uniform rate of flow cannot be determined from the flow chart, due to the time scale being too small, and*

(c) *the variables change antipathetically.*

The case for two variables has been discussed in Appendix 5. Equally common in actual practice is the case, where the two variables in vibrating flow vary inversely. This case must also be examined, before the degree of latitude in substitution can be determined in the general case. (See Flow Chart No. 5.)



Flow Chart No. 5.

In this case the true total quantity, Q, passing in time, t+at, $=K\,at\sqrt{rXY}+Kt\sqrt{sXY}=Kt\sqrt{XY}\,(a\sqrt{r}+\sqrt{s})$ cu. ft. .... (32). The means of the variables, the periods, "at" and "t," being too short to be represented clearly on the ordinary flow chart, are obtained by taking the arithmetic means of successive maximum and minimum readings.

$\therefore$ The means are $\frac{X\,(1+r)}{2}$ and $\frac{Y\,(1+s)}{2}$ respectively.

$\therefore$ The approximate total quantity, Q, in time, "at"+"t,"

$$=K(at+t)\sqrt{\frac{XY}{4}(1+r)(1+s)}$$

$$=Kt\sqrt{XY}(a+1)\frac{\sqrt{(1+r)(1+s)}}{2}\text{ cu. ft. .....}\quad(33)$$

$$\therefore \text{ The Error Ratio, } \frac{\text{Approximate Total Quantity, } Q_1}{\text{True Total Quantity, } Q} = \frac{(a+1)\sqrt{(1+r)\ (1+s)}}{2\ (a\sqrt{r}+\sqrt{s})} \quad \ldots\ldots\ldots\ldots\ldots \quad (34)$$

The Percentage Error in measurement :—

$$= \left\{ \frac{\{(a+1)\sqrt{(1+r)\ (1+s)} - 2\ (a\sqrt{r}+\sqrt{s})\}}{2\ (a\sqrt{r}+\sqrt{s})} \right\} \times 100\% \ldots\ldots \quad (35)$$

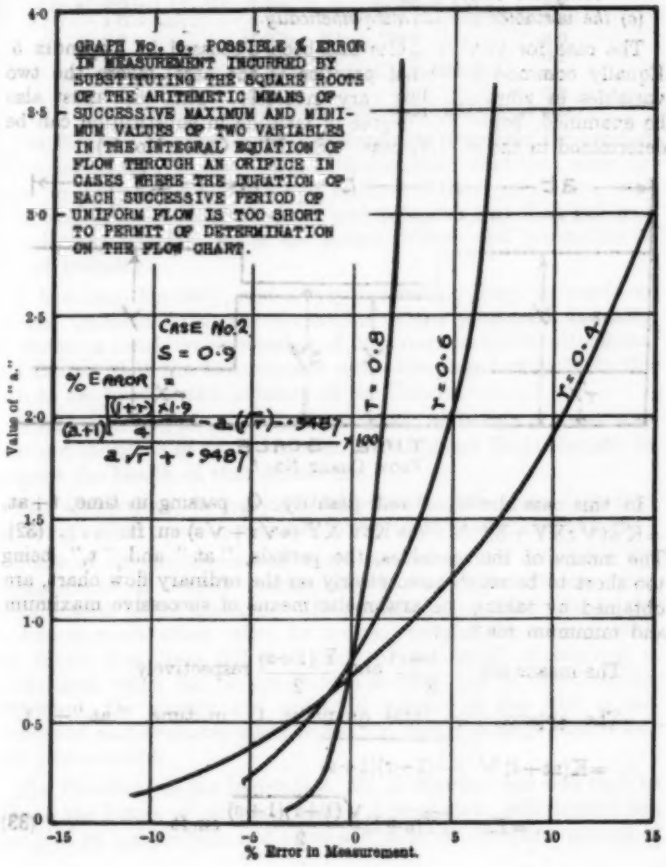

GRAPH No. 6. POSSIBLE % ERROR IN MEASUREMENT INCURRED BY SUBSTITUTING THE SQUARE ROOTS OF THE ARITHMETIC MEANS OF SUCCESSIVE MAXIMUM AND MINIMUM VALUES OF TWO VARIABLES IN THE INTEGRAL EQUATION OF FLOW THROUGH AN ORIFICE IN CASES WHERE THE DURATION OF EACH SUCCESSIVE PERIOD OF UNIFORM FLOW IS TOO SHORT TO PERMIT OF DETERMINATION ON THE FLOW CHART.
CASE No. 2
S = 0·9
r = 0·8
r = 0·6
r = 0·4
Value of "a."
% Error in Measurement.
4·0
3·5
3·0
2·5
2·0
1·5
1·0
0·5
0
-15
-10
-5
0
5
10
15

Table No. VI.

Percentage Error in Measurement, Incurred by Substituting the Square Roots of the Arithmetic Means of Successive Maximum and Minimum Values of Two Variables in the Integral Equation of Flow through an Orifice, in Cases where the Duration of Each Successive Period of Uniform Flow is too Short to Permit of Determination.

Case No. 2.

Values of "s" in this table is 0·9.

Values of "a."	Values of "r."		
	0·4	0·6	0·8
0·2	—9·0	—5·2	—1·55
0·4	—5·0	—3·0	—0·9
0·6	—1·7	—1·3	—0·4
0·8	0·9	0·1	0·0
1·0	3·1	1·2	0·3
1·5	7·4	3·3	0·9
2·0	10·5	4·7	1·3
3·0	14·7	6·5	1·9

THE INSTITUTION OF PETROLEUM TECHNOLOGISTS. TRINIDAD BRANCH.

SECOND ANNUAL DINNER.

THE SECOND ANNUAL DINNER of the Trinidad Branch of the Institution of Petroleum Technologists was held on October 15th, 1932, at the Queen's Park Hotel, Port of Spain. Mr. A. F. Dabell, M.I.Mech.E., was in the chair. The principal guest was His Excellency the Acting-Governor, the Hon. S. M. Grier, C.M.G., who was attended by Mr. A. J. de Boissiere, A.D.C.

"The King."

The toast of "The King" was loyally honoured.

"The Institution of Petroleum Technologists."

His Excellency the Acting-Governor, in proposing the toast of "The Institution of Petroleum Technologists," said that since he came to Trinidad one thing had impressed itself upon him, and that was that the future welfare and prosperity of Trinidad was very largely wrapped up in the future welfare and prosperity of the oil industry.

It had been his duty, and a very interesting duty, to meet, on various occasions, the representatives of the petroleum industry to discuss a considerable number of important subjects with them, and he felt that the Government was extremely fortunate in the men at the head of this industry in the Colony.

It was with real pleasure that he wished, on behalf of those who were not members of the Institution of Petroleum Technologists, to propose the health of that Institution.

The Chairman, in replying, said that he was again honoured by being called upon to respond to the toast of the Institution.

Force of circumstances and world conditions had called for the restriction of oil output—particularly in the United States—from wells flowing under pressure. The application of restriction to the best economical effect called for a close study of the subject, with the result that from different parts of the world declaration is made that, when the output from a flowing well is unreasonably restricted, the energy and potential output of the well is not conserved and available when called for, but to a large extent lost and irrecoverable.

The President of the Institution, Mr. J. Kewley, has said that he thinks the future of our race, taking a long view, will depend less and less on competition and more and more on scientific control of

conditions. By this it is to be assumed that effort will be made to balance supply and demand to the abandonment of the survival of the fittest, and with that will pass the whole structure of our pre-war finance.

If it be possible for the human mind to cope with this huge problem, we may then come to an era when we who endeavour to invent and improve, may feel that our labours are not solely for the benefit of that section of the community which is sufficiently speculative to invest its money in the Oil Industry. Then, perhaps, by a system of endowed leisure or alternatively by a higher standard of living, man, at large, will enjoy the benefits of victories over Nature.

If he had touched upon more serious matters than befitted the occasion, he apologised, but he thought that opportunities are rare when such matter can be fittingly put forward without risk, and it is to our discredit that we are apt to view the troubles of our colleagues with an increasing philosophic calm.

Maybe, next year His Excellency would not be in such generous mood and might use the words of Kipling:—

"Ye have read, ye have heard, ye have thought," he said,
"and the tale is yet to run:
"By the worth of the body that once ye had, give answer—
what ha' ye done?"

He took the opportunity of tendering the thanks of the Industry to the Government of Trinidad for the freedom enjoyed by the absence of fettering control, and for their encouragement of enterprise.

For the development of the JOURNAL, the Institution's greatest asset, gratitude is due to Dr. Dunstan.

It was the duty of all to remember the Benevolent Fund, our greatest liability.

It is to Mr. Reid, our Honorary Secretary, that their thanks were due for the work involved in the organisation of this meeting.

On behalf of the Institution, he thanked His Excellency for the kind way in which he had proposed this toast, and expressed appreciation of the honour he had done them in being present.

"The Industries of Trinidad."

Mr. G. H. Scott, in proposing the toast of "The Industries of Trinidad," said we are passing through a period of depression without parallel in the last century. In retrospect it is extraordinary that it did not have much more violent repercussions.

The economic history of the world shows that periods of depression alternate with periods of prosperity and he felt that in arriving at an idea of the returns of industry one should work on an average over these periods, rather than base the calculations on periods of prosperity alone.

A consoling fact is that previous periods of depression have been followed immediately by periods of prosperity and it was certain that the lessons learnt have placed the Industries of Trinidad in such a position that they will reap the full benefits from the better times that are coming.

Mr. J. Forbes, in replying, said that as individuals they could take personal pride in being so closely connected with the development of our most important industry, and he ventured to hope that their interests would extend in other directions and thus share in making the Island of Trinidad also proud to be a self-supporting unit of the Oldest Colonies in our Great Empire.

"Our Guests."

Mr. J. L. Harris, in proposing the toast of "Our Guests," said it was a very definite pleasure for him to welcome all the guests and he would ask the members to rise and drink to the toast of "Our Guests," coupled with the name of Mr. Justice Gilchrist.

Mr. Justice Gilchrist, in replying to the toast of "Our Guests," said that words were inadequate to express their kindly feelings towards their hosts for the excellent entertainment they have provided.

BOOKS RECEIVED

INDEX TO A.S.T.M. STANDARDS AND TENTATIVE STANDARDS, October, 1932.

The current Index to the A.S.T.M. Standards is a very convenient reference for ascertaining whether or not a standard has been issued on a specific subject and if so in which publication of the Society it appears.

Copies may be obtained free of charge on application to the A.S.T.M., 1315, Spruce Street, Philadelphia, Pa., U.S.A.

REPORT OF FURTHER TESTS BY THE DIRECTOR OF FUEL RESEARCH ON THE TURNER RETORT, INSTALLED AT THE WORKS OF THE COMAC OIL CO., LTD., COALBURN, LANCASHIRE. London, H.M. Stationery Office, 1932. Pp. viii + 35. 9d. net.

The first test of this retort was made in 1929, the present tests being carried out from November 13 to December 3, 1930. In the first test, alternating pressure was used and in the second, a constant pressure of 0·33 lb./sq. in. above atmospheric. The yield and quality of the tar was substantially the same in each test, but the separation of the tar-water mixture was not so good when constant pressure was used.

PETROLEUM VADEMECUM. R. Schwarz. 9th Edn., 2 Vols., Vienna, *Verlag für Fachliteratur*, 1932. Rm. 24.

The ninth edition of this useful reference book follows the lines of its predecessor. The basis of the book is in German, but the headings of the conversion tables, etc., are given in English and French as well, and the index is in the three languages.

The tables include weights and measures, specific gravity, viscosity, etc., and a useful summary is given of Customs duties levied in various countries. The nomenclature of petroleum is dealt with in a table giving the names of various products in a number of languages. Statistics of the production of petroleum are given in detail.